

CORDEX-WRF module: version 2

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1 Introduction

There are some variables in the CORDEX list, that might require an agreement within the community in how to compute / infer / diagnose them. With this in mind, and following the previous work published in ('*Geoscientific Model Development (GMD)*' [Fita et al., 2019](#), hereafter *Fita19*), here is presented a new version of the module which include some new variables

2 Variables

Some of the new variables are needed for the new CORDEX-list of variables, some others are included as seen as potentially useful for some communities.

2.1 zmla: Boundary layer height

This variable is provided as a diagnostics by almost all the planetary boundary layer (pbl) schemes implemented in the atmospheric models. However, because these schemes are constructed over different assumptions and set of equations. Therefore it makes not possible to directly compare values among models (or even within the same model, using different pbl schemes).

In the first version (*Fita19*), a unique methodology was provided. In this update, a new one is introduced. At the same time, due to the existence of 2 different methodologies, a new flag called '**zmlagen_diag**' is introduced, with which user select the preferred method of diagnose the generic boundary layer height, being:

- **zmlage_diag** = 1: vertical, theta-e based methodology from ([Nielsen-Gammon et al., 2008](#)) as it was in previous version of the module
- **zmlage_diag** = 2: bulk methodology using the Richardson number after ([Vogelezang and Holtslag, 1996](#); [Seidel et al., 2004](#)) [default value]

See results in figure [1](#).

2.1.1 Nielsen-Gammon08

After ([Nielsen-Gammon et al., 2008](#)). The method consists in defining the height of the PBL as the first level in the mixed layer (ML) where potential temperature exceeds the minimum potential ML temperature by more than 1.5 K. It has been implemented using the definitions given below:

1. Mixed layer depth (MLD) is defined as the model level (k_{MLD}) starting from the second model level at which the variation of the mixing ratio ($qv(k)$, normalized with its value at the first level) exceeds some predefined threshold value ($qv(1)$): $\frac{|qv(k_{MLD})-qv(1)|}{qv(1)} > \delta qv$ (here applied a $\delta qv = 0.1$)
2. Within the MLD the value with the minimum potential temperature is taken as: $\theta_{min_{MLD}} = \min[\theta(1), \dots, \theta(k_{MLD})]$
3. The level of the pbl height (k_{zmla}) is the level at which the maximum variation of potential temperature within the MLD exceeds some predefined threshold value: $\theta(k_{zmla}) - \theta_{min_{MLD}} > \delta\theta$, (here $\delta\theta = 1.5 K$)
4. The pbl height ($zmla$) is obtained using the geopotential height zg at the calculated k_{zmla} level above the ground ($zagl$): $zmla = zagl(k_{zmla}) = zg(k_{zmla})/g - HGT$, with HGT being surface elevation height above sea level.

No general rule has been applied to determine the correct value of δqv used to determine MLD. It can be determined by the namelist parameters **zmlagen_dqv** for δqv (default value 0.1) and **zmlagen_dtheta** for $\delta\theta$ (default value 1.5 K). When comparing this implementation with the $zmla$ directly provided by WRF's Mellor-Yamada Nakanishi and Niino Level 2.5 PBL scheme (MYNN2.5 [Nakanishi and Niino, 2006](#)) in WRF model (shown in figure 9 in *Fita19*). In general the generic estimation produces a higher pbl (a panel) with lower values during night (b panel). Spatial distributions between both diagnostics are pretty similar.

2.1.2 Bulk zmla

After (Vogelezang and Holtslag, 1996), zmla is computed using the bulk Richardson number. A threshold ($\mathcal{R}i_{thres} = 0.25$) is defined in order to determine the height of the pbl (see equation 1).

$$zmla = \begin{cases} \mathcal{R}i[z] \leq \mathcal{R}i_{thres} < \mathcal{R}i[z+1] \\ or \mathcal{R}i[z] \geq \mathcal{R}i_{thres} > \mathcal{R}i[z+1] \end{cases} \quad (1)$$

Using the bulk-Richardson number as defined in the equation 2

$$\mathcal{R}i = \frac{g/T_v \Delta\theta_v \Delta z}{(\Delta u)^2 + (\Delta v)^2 + 100(u^*)^2} \quad (2)$$

where Bulk Richardson number follows AMS Glossary definition (https://glossary.ametsoc.org/wiki/Bulk_richardson_number) adding the $(u^*)^2$ term as a way to take into account turbulence due to surface friction on neutral boundary layer (eq. 3 in Vogelezang and Holtslag, 1996). g is gravitational acceleration, T_v , absolute virtual temperature, $\Delta\theta_v$, virtual potential temperature difference across a layer of thickness Δz , Δu and Δv are the changes in horizontal wind components across that same layer.

2.2 0-isotherm

Diagnose of the first height from the ground where air-temperature becomes 0 (see results in figure 2).

2.3 ws50m, u50m, v50m

Diagnose at 50 m of wind, temperature and humidity has been introduced in this update. User can set-up the desired height with the namelist parameter `z50m`. Its default value is 50. These diagnostics are directly activated when compiling with the flag `-DCORDEXDIAG`.

5 new variables have been introduced:

- WSZ50: 50m wind speed, ms^{-1}
- UZ50: Eastward 50 m wind speed, ms^{-1}
- VZ50: Northward 50 m wind speed, ms^{-1}
- TAZ50: 50 m air temperature, K
- QVZ50: 50 m water vapour, $kgkg^{-1}$

2.3.1 ws50m, u50m, v50m

Following Monin-Obukhov Similarity theory (see Box 1 for remarks) a diagnose to extrapolate winds (for the `ua100m`, `va100m` diagnostic) for winds below 80 m was introduced in the module. The wind at given height is extrapolated following turbulent mechanisms. As it is shown in equation 3, surface wind speed is used as surrogate to estimate 100 m wind direction ($\theta_{10} = \tan^{-1}(uas, vas)$), without considering Eckman pumping, or other effects on wind direction). In this implementation u_* in similarity theory is taken as model estimates of UST, Monin-Obukhov length (\mathcal{L}_O), roughness length (z_0) and thermal time-varying roughness length ZNT.

$$\begin{aligned} wss_{100} &= \frac{UST}{\kappa} \left(\ln \left(\frac{100}{z_0} \right) + \Psi_M \left(\frac{100}{\mathcal{L}_O} \right) \right) \\ \mathcal{L}_O &= \frac{-UST^3 T_v}{\kappa g Q_0} \quad (Obukhov \ length) \\ \Psi_M \left(\frac{z}{\mathcal{L}_O} \right) &= \begin{cases} \frac{4.7z}{\mathcal{L}_O} & \frac{z}{\mathcal{L}_O} > 0 \quad (sTable) \\ \ln \left[\left(\frac{1+X^2}{2} \right) \left(\frac{1+X}{2} \right)^2 \right] - 2 \tan^{-1}(X) + \frac{\pi}{2} & \frac{z}{\mathcal{L}_O} < 0 \quad (unsTable) \end{cases} \end{aligned} \quad (3)$$

0006: Base Marambio

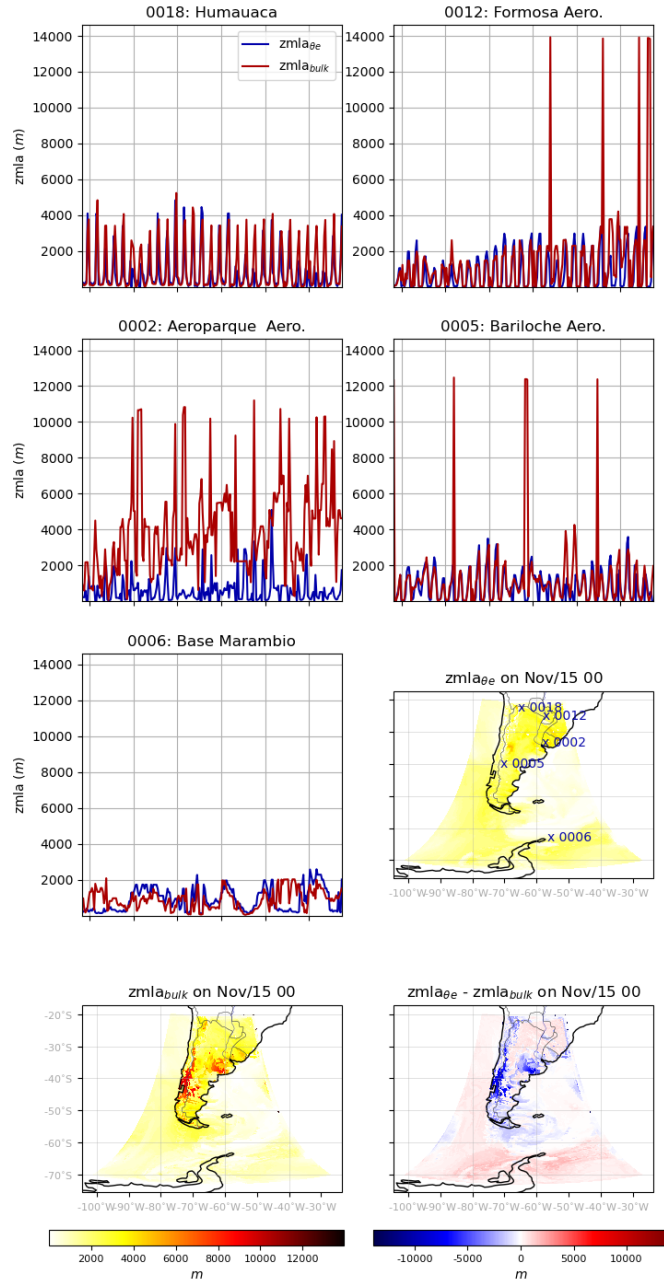


Figure 1: Evolution of generic boundary layer (zmla) by the two methods (theta-e, blue; bulk-Richardson, red) at different stations and on the 15th of November at 00 UTC for all the domain, for the diagnostics and the differences between them

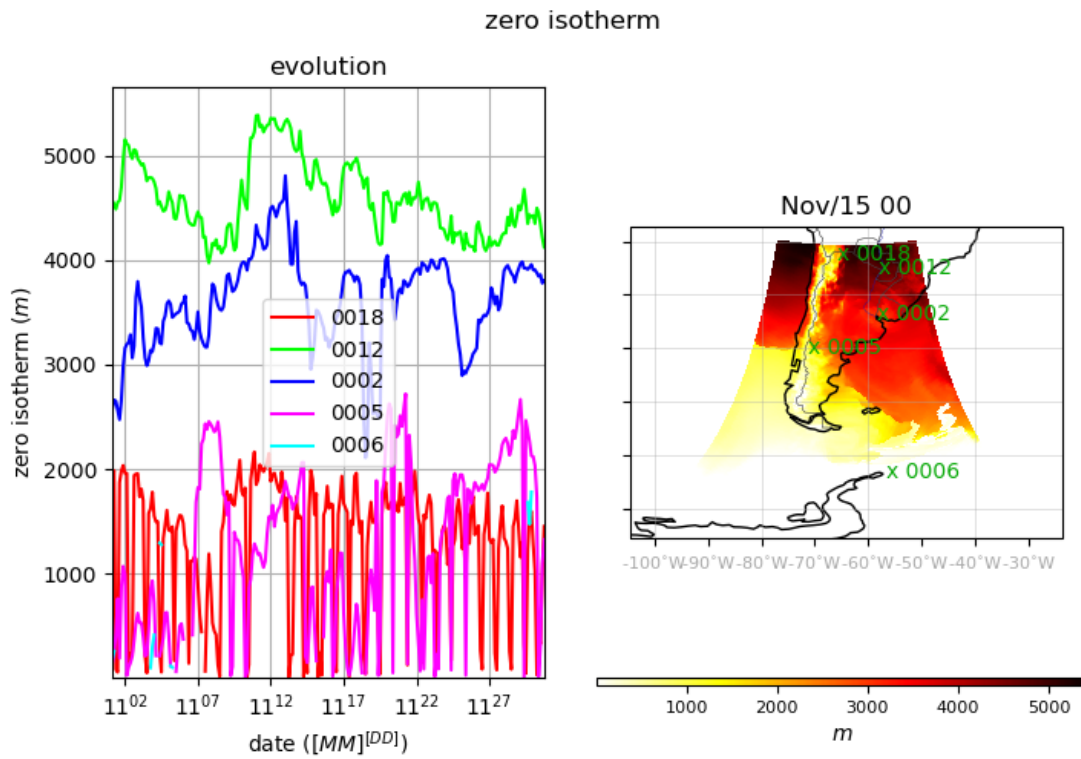


Figure 2: Evolution of zero isotherm ($z|_{ta=0^{\circ}C}$) at different stations and on the 15th of November at 00 UTC for all the domain

$$X = \left(1 - \frac{15z}{\mathcal{L}_O}\right)^{1/4}$$

$$\theta_{10} = \text{atan}\left(\frac{V10}{U10}\right) \vec{v}\vec{a}_{100} = \begin{cases} ua_{100} = wss_{100} \cos(\theta_{10}) \\ va_{100} = wss_{100} \sin(\theta_{10}) \end{cases}$$

wss_{100} : wind speed at 100 m (ms^{-1}), where Ψ_M : stability function after (Businger et al., 1971), UST : u^* in similarity theory (ms^{-1}), z_0 : roughness length (m), $U10, V10$: 10-m wind speed, θ_{10} : 10-m wind speed direction (rad), ua_{100} : 100 m eastward wind speed, va_{100} : 100 m northward wind speed (note the absence of correction in wind direction to Ekman pumping or other turbulence effects)

Figure 6 from Fita19 shows different preliminary results using the three different approximations for wind gust estimation. It is illustrated (a panel) how wind-gusts are larger than the 10-m diagnostic winds, and also the difference is larger when using Monin-Obukhov method compared to the two others methods. Certain problems (too small Monin-Obukhov length) are recognized when applying Monin-Obukhov for extrapolating wind at 100 m, which is shown in panel b, where wind gusts appear to be strong as $80 ms^{-1}$. Therefore user is advised to use this method with care.

Here one should notice that some of the pbl-related variables ($UST, z_0, U10, V10, \theta_{10}, \dots$) will be model / scheme dependent.

2.3.2 ta50m, hus50m

To diagnose temperature and humidity at relatively close to the surface ($z < 80 m$), is suggested to use the Monin-Obukhov Similarity Theory (see remarks of box 1), but adapting the equations to these variables.

Limitations of Monin-Obukhov Similarity Theory

The implemented equations are the ones from Businger et al. (1971). These equations only apply within certain ranges of the fraction z/\mathcal{L}_0 , being z : height and \mathcal{L}_0 : Monin-Obukhov length. The turbulent assumptions from which, one can vertically extrapolate scalars, must be within the turbulence-driven layer of the atmosphere, which happens to be (accordingly to Bussinger) within the range ($z/\mathcal{L}_0 > -2., z/\mathcal{L}_0 < 1.$).

According to this limitation, diagnose uses models' 3-dimensional zg, ta, qv to linearly extrapolate ta_{50m} and hus_{50m} for the grid points that 50 m above ground lays outside the TKE-driven turbulence layer

One should be aware, that in order to proceed, we need to obtain the slope of the vertical profile of the desired variable: u^* for wind, ta^* for temperature and qv^* for humidity and that at the surface whereas $u_0 = 0$, for $ta_0, qv_0 \neq 0$. Models tend to provide u^* , but not ta^*, qv^* , therefore, it would be necessary to perform a two step methodology in order to get the necessary values, needed to estimate ta and qv at a desired height z_d (here we present the example for $ta(z_d)$):

1. Compute the increment (e.g. $\Delta ta' = ta(k+1) - ta(k)$) of the variable respect a known heights (at vertical levels k and $k+1$) from the 3-dimensional atmospheric temperature field
2. Infer ta^*
3. Compute the increment between one of the 3-dimensional temperatures and the desired height using ta^* (e.g. $\Delta ta'' = ta(k) - ta(z_d)$), to obtain ta_0
4. Obtain $ta(z_d)$

The general equation for the vertical profile of temperature and humidity at the surface layer of the PBL follows the equation 4

$$\bar{\chi}(z) - \bar{\chi}_0 = \frac{\chi^*}{\kappa} \left[\ln\left(\frac{z}{z_0\chi}\right) - \Psi_{\Xi}\left(\frac{z}{\mathcal{L}_O}\right) \right] \quad (4)$$

where $\chi = ta, qv$, for temperature and humidity and in this case will be the instantaneous values of the variable at the grid point during the integration of the model (T (previously converted to actual temperature) and QVAPOR),

Ψ_{Ξ} stability function, with dependency on the stability and with different options for the profiles to use, here for completeness, Businger profiles will be used. Here, the formulations for scalars will be used (ta and qv will be treated as scalars fields). $z_0\chi$ can be replaced by $0.1z_0$ (roughness length) without introducing too much error ($z_0ta = z_0qv = 0.1z_0$).

The stability functions for temperature and humidity (being the same) are shown in equation 5

$$\Psi_{ta,qv} \begin{cases} 1 - \phi_{ta,qv} \left(\frac{z}{\mathcal{L}_O} \right) & \frac{z}{\mathcal{L}_O} \geq 0 \\ \ln \left[\left(\frac{1+\xi}{2} \right)^2 \right] & \frac{z}{\mathcal{L}_O} < 0 \end{cases} \quad (5)$$

where $\xi = \phi_{ta,qv}^{-1}$ and $\phi_{ta,qv}$ are the universal functions.

There are different universal functions depending on the works and observations used. Here the ones closer to the same used for the winds will be used, which will correspond to the ones purposed by (Businger et al., 1971, expressed in equation 6).

$$\kappa = 0.35; \phi_{ta,qv} = \begin{cases} 0.74(1 - 9\frac{z}{\mathcal{L}_O})^{-1/2} & -2 < \frac{z}{\mathcal{L}_O} < 0 \text{ (unstable)} \\ 0.74 & \mathcal{L}_O = 0 \text{ (neutral)} \\ 0.74 + 4.7\frac{z}{\mathcal{L}_O} & 0 < \frac{z}{\mathcal{L}_O} < 1 \text{ (stable)} \end{cases} \quad (6)$$

To obtain χ^* , one derives it from the $\Delta\bar{\chi}$ equation 7

$$\begin{aligned} \Delta\bar{\chi} &= (\bar{\chi}(k+1) + \bar{\chi}_0) - (\bar{\chi}(k) + \bar{\chi}_0) = \bar{\chi}(k+1) - \bar{\chi}(k) = & (7) \\ &= \frac{\chi^*}{\kappa} \left[\ln \left(\frac{z(k+1)}{z_0} \right) - \Psi_{\Xi} \left(\frac{z(k+1)}{\mathcal{L}_O} \right) \right] - \frac{\chi^*}{\kappa} \left[\ln \left(\frac{z(k)}{z_0} \right) - \Psi_{\Xi} \left(\frac{z(k)}{\mathcal{L}_O} \right) \right] \\ &= \frac{\chi^*}{\kappa} \left[\ln \left(\frac{z(k+1)}{z_0} \right) - \ln \left(\frac{z(k)}{z_0} \right) - \Psi_{\Xi} \left(\frac{z(k+1)}{\mathcal{L}_O} \right) + \Psi_{\Xi} \left(\frac{z(k)}{\mathcal{L}_O} \right) \right] \\ &= \frac{\chi^*}{\kappa} \left[\ln \left(\frac{z(k+1)}{z_0} \frac{z_0}{z(k)} \right) - \Psi_{\Xi} \left(\frac{z(k+1)}{\mathcal{L}_O} \right) + \Psi_{\Xi} \left(\frac{z(k)}{\mathcal{L}_O} \right) \right] \\ &= \frac{\chi^*}{\kappa} \left[\ln \left(\frac{z(k+1)}{z(k)} \right) - \Psi_{\Xi} \left(\frac{z(k+1)}{\mathcal{L}_O} \right) + \Psi_{\Xi} \left(\frac{z(k)}{\mathcal{L}_O} \right) \right] \end{aligned}$$

Using known heights $z(k+1)$, $z(k)$ and the values of $\bar{\chi}(k)$, $\bar{\chi}(k+1)$ from the model levels, one can reduce χ^* as it is shown in equation 8

$$\chi^* = \kappa \frac{\bar{\chi}(k+1) - \bar{\chi}(k)}{\ln \left(\frac{z(k+1)}{z(k)} \right) - \Psi_{\Xi} \left(\frac{z(k+1)}{\mathcal{L}_O} \right) + \Psi_{\Xi} \left(\frac{z(k)}{\mathcal{L}_O} \right)} \quad (8)$$

Using again the $\Delta\bar{\chi}$ for de desired height z_d and with the recently found χ^* , one can obtain the actual value of $\bar{\chi}(z_d)$ (and also retrieve χ_0) as it is shown in equation 9

$$\begin{aligned} \Delta\bar{\chi} &= \bar{\chi}(k) - \bar{\chi}(z_d) & (9) \\ &= \frac{\chi^*}{\kappa} \left[\ln \left(\frac{z(k)}{z_d} \right) - \Psi_{\Xi} \left(\frac{z(k)}{\mathcal{L}_O} \right) + \Psi_{\Xi} \left(\frac{z_d}{\mathcal{L}_O} \right) \right] \\ \bar{\chi}(z_d) &= \frac{\chi^*}{\kappa} \left[\ln \left(\frac{z(k)}{z_d} \right) - \Psi_{\Xi} \left(\frac{z(k)}{\mathcal{L}_O} \right) + \Psi_{\Xi} \left(\frac{z_d}{\mathcal{L}_O} \right) \right] + \bar{\chi}(k) \end{aligned}$$

And for the case where $z_d > z(k)$ in equation 10

$$\begin{aligned} \Delta\bar{\chi} &= \bar{\chi}(z_d) - \bar{\chi}(k) & (10) \\ \bar{\chi}(z_d) &= \frac{\chi^*}{\kappa} \left[\ln \left(\frac{z_d}{z(k)} \right) - \Psi_{\Xi} \left(\frac{z_d}{\mathcal{L}_O} \right) + \Psi_{\Xi} \left(\frac{z(k)}{\mathcal{L}_O} \right) \right] + \bar{\chi}(k) \end{aligned}$$

Box 1: IMPORTANT REMARK about the Monin-Obukhov based diagnostics

Monin-Obukhov theory is used as an approximation to the estimation of the values of variables within the ‘surface layer’ of the *Planetary Boundary Layer* (PBL). One must be aware, that Monin-Obukhov theory and its associated vertical profiles are designed to be universal depictions of the dynamics of chaos based on *temporal-means*. Results should be taken with caution when used in atmospheric models to diagnose certain values.

- Used only within the ‘surface layer’ of the planetary boundary layer. This surface layer, is not universal and it will depend on a large number of conditions such as: stability, surface characteristics, existing canopy, among others. There is not an actual way to determine the end of the end of the layer. Bearing this in mind, under ‘normal’ conditions, should not be used above 80 m (maybe far less in stable nights)
- Profiles of the theory are not providing ‘instantaneous’ descriptions of the actual conditions of the atmosphere. These profiles although attempt to be ‘universal’, strongly rely on the observations used to extract them. Also, they are used as temporal mean representations of the chaotic behavior of the atmosphere. These mean representations are averages computed for high frequency measurements (order of Hz) for time-windows of 10 to 30 minutes.
- Due to the lack of proper observations of humidity, the vertical profiles of the field are similar to the ones from the temperature, by using the profiles for scalar variables.
- Therefore, diagnostics based on Monin-Obukhov theory (or similar), should take with caution. Since, from the modeling perspective:
 1. They are used to provide instantaneous values
 2. Distinction among ‘ $PBL_{surf\ layer} - PBL - free\ atmosphere$ ’ is strongly dependent of models
 3. In some cases, there is no information about height of the canopy of the grid cell, and how PBL is interpreted in the areas within / outside the canopy
- There might be vertical profiles for layers above the surface layer and still within the PBL, but these profiles would not follow Monin-Obukhov theory.
- In the cases, where desired heights are outside the PBL, the values of the variables at the desired heights could be directly interpolated from the closest pair of vertical layers of the atmosphere
- There are some vertical profiles for the entire PBL (see for example [Ulke, 2000](#)), but they will not be considered (yet)

acknowledgments: Thanks to Dr. Marisa Gassman and Natalia Tonti (DCAO, UBA, Argentina) for their suggestions, comments and explanations

In order to avoid non consistent values, diagnosed values $\bar{\chi}(z_d)$ are constrained within the values at model’s first layer values $ta|_{k=1}$, $qv|_{k=1}$ and the second one $ta|_{k=2}$, $qv|_{k=2}$. In that cases, the value at 50 m is given as the closest one ($k_{closest}$), following the equations at [11](#)

$$\left\{ \begin{array}{l}
 tamin = \min(ta|_{k=1}, ta|_{k=2}) \\
 qvmin = \min(qv|_{k=1}, qv|_{k=2}) \\
 tamax = \max(ta|_{k=1}, ta|_{k=2}) \\
 qvmax = \max(qv|_{k=1}, qv|_{k=2}) \\
 k_{closest} \rightarrow \min(abs(z|_{k=1} - 50.), abs(z|_{k=2} - 50.))
 \end{array} \right.$$

$$\begin{aligned}
 ta_{50m} &< tamin \rightarrow ta_{50m} = ta|_{k=k_{closest}} \\
 hus_{50m} &< qvmin \rightarrow hus_{50m} = qv|_{k=k_{closest}} \\
 ta_{50m} &> tamax \rightarrow ta_{50m} = ta|_{k=k_{closest}} \\
 hus_{50m} &> qvmax \rightarrow hus_{50m} = qv|_{k=k_{closest}}
 \end{aligned} \tag{11}$$

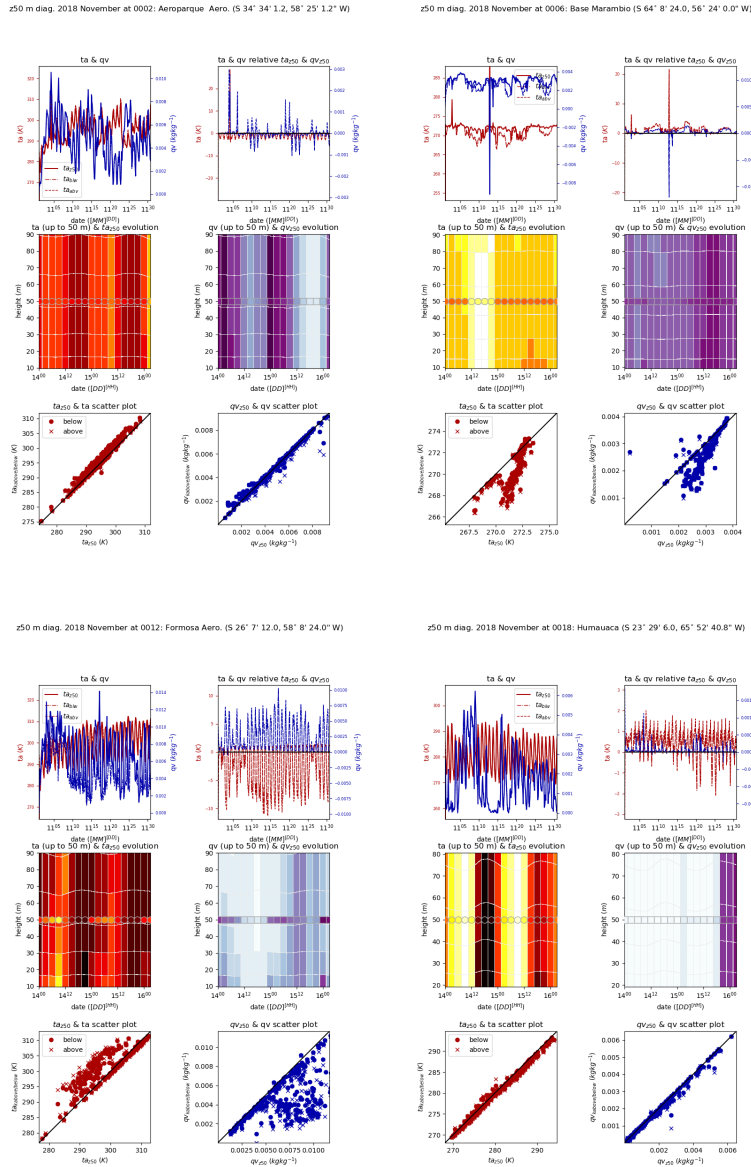


Figure 3: Comparison of air-temperature (ta_{z50}) and mixing ratio (qv_{z50}) diagnostics at 50 m following Monin-Obukhov Similarity Theory and vertically closest atmospheric values (below, above 50 m) for a WRF simulation on November 2018 at 5 different Argentinean locations: *Aeroparque airport* (0002 station, top left), *Antarctic Marambio base* (0006 station, top right), *Formosa airport* (0012 station, bottom left) and *Humauaca* (0018 station, bottom right). Top left panel: monthly time-series air temperature (ta , red, left y-axis), mixing ratio (qv , blue, right y-axis). Top right panel: values at the vertical level above/below 50 m respect the diagnostic value. Middle panels: vertical profile evolution around 50 m with diagnostics at 50 m as colored markers, and vertical WRF values as shading. Bottom left panel: Scatter diagram for diagnosed temperatures (x-axis) respect atmospheric values below/above 50 m (y-axis). Bottom right panel: Scatter diagram for diagnosed mixing ratios (x-axis) respect atmospheric values below/above 50 m (y-axis). Different scales and ranges are used in each figure

2.4 iutmean, ivtmean

Vertically integrated horizontal transport of water vapour is a common diagnostic in climate studies. Here is introduced as the mean value between output time-steps (adding the individual amounts during model integration time-steps) as it is shown in equation 12 and figure 4. This variable is activated with compilation flag `-DCDXWRF=1`

$$i\chi t = \frac{MU + MUB}{g} \sum_{iz=1}^{e_{vert}} \chi * QVAPOR[iz](DNW[iz]) \quad (12)$$

where $\chi = u, v$ being each of the wind components.

Two new variables will appear at the `wrfcdx (auxhis9)` output file:

- IUTMEAN: mean vertically integrated eastward transport of water vapour, $kgm^{-1}s^{-1}$
- IVTMEAN: mean vertically integrated northward transport of water vapour, $kgm^{-1}s^{-1}$

2.5 tas_hm, hurs_hm

The diagnostics for 2-m temperature and humidity from ‘*Modèle de Circulation Générale du LMD*’ (LMDZ, <https://lmdz.lmd.jussieu.fr> Hourdin et al., 2006) are introduced into WRF as additional diagnostics. These implementations follow an iterative methodology following (Hess et al., 1995). These variables are activated when compiling the module with the pre-comilation flag `-DCORDEXDIAG`

Two new variables are introduced:

- TAS_HM: Corrector-calculator (Hess-McAvaney, 1995) 2m temperature, K
- QVS_HM: Corrector-calculator (Hess-McAvaney, 1995) 2m water vapor mixing ratio, K

It follows a 2-step methodology:

1. First estimate using the Dyer-Businger formulation
2. Corrector of the estimates using the Louis formulation

In more detail (following Hess et al., 1995):

1. Vertically integrating the Monin-Obukhov equations for temperature, humidity and wind, one obtains the vertical profiles for each variable shown in equations 13 to 15

$$\kappa \frac{wss}{u^*} = \ln\left(\frac{z}{z_0}\right) - \Psi_M\left(\frac{z}{\mathcal{L}_0}\right) + \Psi_M\left(\frac{z_0}{\mathcal{L}_0}\right) = \mathcal{F}_M \quad (13)$$

$$\kappa \frac{\Theta - \Theta_0}{\Theta^*} = \ln\left(\frac{z}{z_H}\right) - \Psi_H\left(\frac{z}{\mathcal{L}_0}\right) + \Psi_H\left(\frac{z_H}{\mathcal{L}_0}\right) = \mathcal{F}_H \quad (14)$$

$$\kappa \frac{Q - Q_0}{Q^*} = \ln\left(\frac{z}{z_Q}\right) - \Psi_Q\left(\frac{z}{\mathcal{L}_0}\right) + \Psi_Q\left(\frac{z_Q}{\mathcal{L}_0}\right) = \mathcal{F}_Q \quad (15)$$

where wss : horizontal wind speed, $(u^*)^2 = \tau_0/\rho$: friction velocity with τ_0 : surface sharing stress, ρ : air density, $\Theta^* = -H_0/\rho C_p u^*$: temperature scale, H_0 : surface heat flux, C_p : specific heat of air at constant pressure, $Q^* = -E_0/\rho u^*$: humidity scale, E_0 : surface evaporative flux, $\mathcal{L}_0 = (u^*)^2/\kappa g/\Theta_{0v}[\Theta^*(1+0.61\Theta Q_0)+0.61\Theta_0\Theta^*]$: Obukhov length, g : gravity, $\Theta_{0v} = T_0(P_r/P_0)^{R/C_p}(1+0.61\Theta_0)$: surface virtual potential temperature, T_0 : surface temperature, P_0 : surface pressure, $P_r = 1000 \text{ hPa}$: reference pressure, R : gas constant for air, Ψ_M, Ψ_H, Ψ_Q : stability functions (empirically determined Dyer, 1974) as integrated counterparts of the vertical profiles in Monin-Obukhov equations $\phi_M, \phi_H, \phi_Q, z_0, z_H, z_Q$: surface roughness lengths for momentum, heat and moisture, χ_0 : value of variable χ at the surface. Accordingly to Kaimal and Finnigan (1994) the experimental validity of these equations is found within $-2 \leq z/\mathcal{L}_0 \leq 1$. Model output at the first vertical layer is used to evaluate u^*, Θ^* and Q^* , using the β -formulation for which $Q_0 - Q(k=1) = D_w(Q_{sat0} - Q(k=1))$: differences between surface and first vertical layer, D_w : efficiency factor, Q_{sat0} : saturated value

WRF/CDX iut, ivt

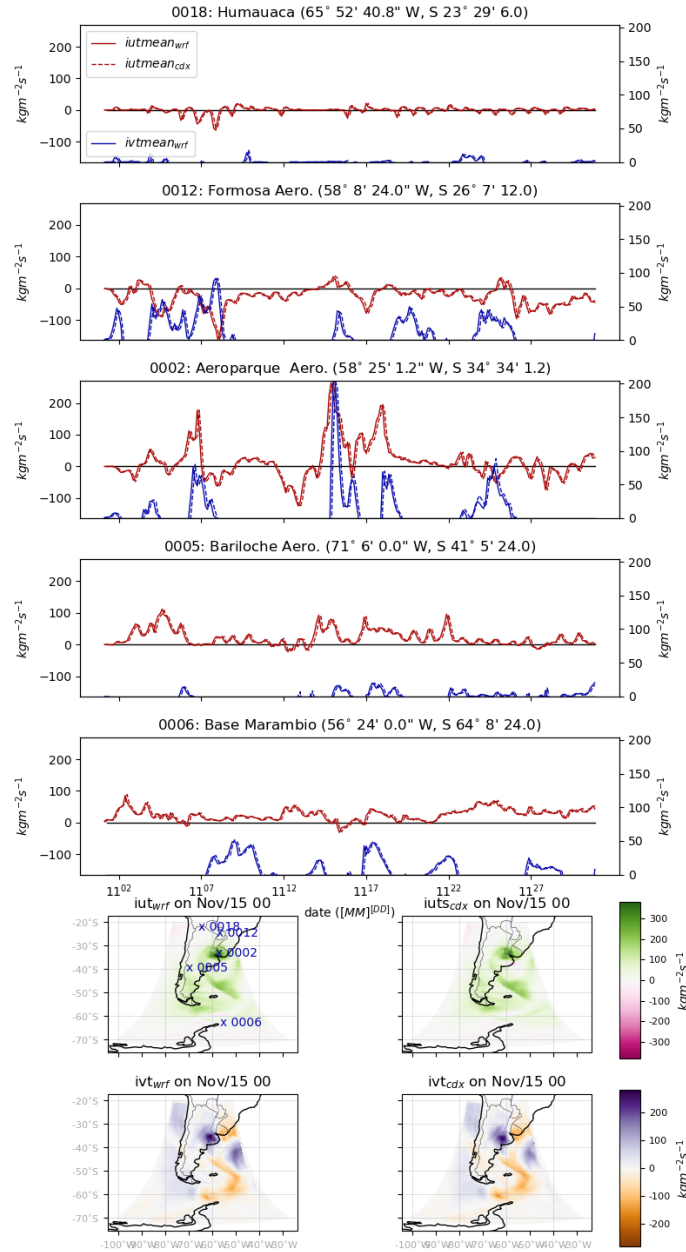


Figure 4: 2018 November 3-hourly evolution of WRF's 3-hourly mean vertically integrated water vapour eastward horizontal transport (iut_{wrf}) and northward horizontal transport (ivt_{wrf}) and CORDEX module based on internal integration values iut_{cdx} , ivt_{cdx} at different locations. Values of iut and ivt on 2011 November 15th at 00 UTC all over the domain

2. Determine the value of the Monin-Obukhov length \mathcal{L}_0
3. Use equations 13 to 15 to predict a value at $z = 1.5m$ and $\Delta\Theta, \Delta Q$ (where $\Delta\chi = \chi(z = 1.5) - \chi_0; \chi = \Theta, Q$), using the stability functions (evaluated at $\zeta = z/\mathcal{L}_0$ and $\zeta_0 = z_0/\mathcal{L}_0$) as in equation 16

$$\Psi_\zeta = \begin{cases} \Psi_M = 2 \ln(1+x) + \ln(1+x^2) - 2 \tan^{-1}(x) \\ \Psi_H(\zeta) = \Psi_Q(\zeta) = 2 \ln(1+x^2) \\ \Psi_M(\zeta) = \Psi_H(\zeta) = \Psi_Q(\zeta) = -5\zeta \end{cases} \begin{array}{l} unstable \\ \\ stable \end{array} \quad (16)$$

where $x = (1 - 16\zeta)^{1/4}$ and $\zeta = z/\mathcal{L}_0$

4. compute the bulk Richardson number Ri_b (see equation 17) at the screen height ($z = 1.5$) and values from 3

$$Ri_b = \frac{g\Delta z}{\Theta_v} \frac{\Delta\Theta_v}{|\Delta\overline{wss}|^2} \quad (17)$$

where $\Delta\Theta_v$: differences in potential virtual temperature and $\Delta\overline{wss}$: differences in horizontal wind speed over the layer

5. Calculate the corrected values of $wss, \Delta\Theta, \Delta Q$ for the layer between the screen layer and the surface using the Louis equations (see 18 to 20, where it is assumed that $z_0 = z_H = z_Q$)

$$\kappa \frac{wss}{u^*} = \frac{\ln(z/z_0)}{\mathcal{F}_M^{1/2}(Ri_b, z/z_0)} \quad (18)$$

$$\kappa \frac{\Theta - \Theta_0}{\Theta^*} = \frac{\ln(z/z_0)}{\mathcal{F}_H(Ri_b, z/z_0)} \mathcal{F}_M^{1/2}(Ri_b, z/z_0) \quad (19)$$

$$\kappa \frac{Q - Q_0}{Q^*} = \frac{\ln(z/z_0)}{\mathcal{F}_Q(Ri_b, z/z_0)} \mathcal{F}_M^{1/2}(Ri_b, z/z_0) \quad (20)$$

where $\mathcal{F}_M = \mathcal{F}_H = \mathcal{F}_Q = 1/(1 + 10Ri_b(1 + 8Ri_b))$ or the most generic formulation shown in (21, equations retrieved from Mahrt et al., 1991)

$$\mathcal{F}(Ri_b, z/z_0) = \begin{cases} (1 + b'Ri_b)^{-2} & stable \\ 1 - \frac{bRi_b}{1+c|Ri_b|^{1/2}} & unstable \end{cases} \quad (21)$$

where $b = 9.4, b' = 4.7, C^* = 7.4$ and

$$c = C^* \kappa^2 b \left(\frac{z}{z_0}\right)^{(1/2)} / \left(\ln\left(\frac{z}{z_0}\right)\right)^2 \quad (22)$$

6. Steps and are repeated using the recently computed Louis profiles until a convergence criteria is meet.

2.5.1 LMDZ implementation

This section attempts to describe how ‘*Modèle de Circulation Générale du LMD*’ (LMDZ Hourdin et al., 2006) GCM model diagnose temperature, humidity and wind at 2 and 10 m.

It is based on Hess et al. (1995) from Dyer-Businger relations and Louis equations. All is done at the subroutine `stdlevvar` from `stdlevvar_mod.F90` module.

1. Using `cdrag` to compute C_m and C_h momentum and heat drag coefficients and Richardson number \mathcal{R}_i , following multiple different methodologies (see more details at section A.1:

- **unstable:** (Louis, 1979) with (Mascart et al., 1995) modifications ($z_0 \neq z_{0h}$), (Louis et al., 1982) and Laurent Li
- **stable:** (Louis, 1979) with (Mascart et al., 1995) modifications ($z_0 \neq z_{0h}$), (Louis et al., 1982) and Laurent Li, (SHARP King et al., 2001) and 1st order Monin-Obukhov theory allowing collapse of turbulence

2. Accordingly to `ok_prescr_ust`) u^* is used to re-compute $Cd_m = (u^*)^2/(wss)^2$
3. Computing star variables: u^* , ta^* , qv^* and \mathcal{L}_0 (Monin-Obukhov length) as in equations 23

$$\begin{aligned}
\theta &= ta|_{k=1} \left(\frac{p_{sfc}}{p|_{k=1}} \right)^{R_d/C_p} \\
u^* &= \sqrt{Cd_m wss^2} \\
\delta_z qv &= \max(qv|_{k=1}, 0) - \max(qv_{sfc}, 0) \\
\delta_z te &= \theta - t_{sfc} \\
\delta_z te &= \max(\delta_z te, \pm 1e^{-10}) \\
te^* &= \frac{Cd_h \delta_z te wss}{u^*} \\
qv^* &= \frac{Cd_h \delta_z qv wss}{u^*} \\
\mathcal{L}_0 &= \frac{(u^*)^2 \theta}{\kappa g te^*}
\end{aligned} \tag{23}$$

4. First guess at 2 m (using `screenp` from `screenp_mod.F90`, see section A.2.1) to obtain $\Delta wss, \Delta \theta, \Delta Q$, resulting on $wss_{ref}, \theta_{ref}, ta_{ref}, qv_{ref}$ (eq. 24)

$$\begin{aligned}
u_{zref} &= \Delta u \\
qv_{zref} &= \max(qv_{sfc}, 0.0) + \Delta qv \\
te_{zref} &= t_{sfc} + \Delta te \\
ta_{zref} &= te_{zref} \left(\frac{p_{sfc}}{p|_{k=1}} \right) - R_d/C_p \\
qv_{zref}^p &= qv_{zref} \\
ta_{zref}^p &= ta_{zref}
\end{aligned} \tag{24}$$

5. corrector-iteration (`niter=2`, configurable from LMDZ model set-up) (using `screenc` from `screenc_mod.F90` to obtain $\Delta^{corr} u$ [at k=1], $\Delta^{corr} te$ [at sfc], $\Delta^{corr} qv$ [at sfc], see section A.3.1) from which $wss_{ref}^{corr}, \theta_{ref}^{corr}, ta_{ref}^{corr}, qv_{ref}^{corr}$ are recomputed (eq. 25)

$$\begin{aligned}
wss_{ref}^{corr} &= \Delta^{corr} u \\
qv_{ref}^{corr} &= \Delta^{corr} qv + \max(qv_{sfc}, 0) \\
te_{ref}^{corr} &= \Delta^{corr} te + t_{sfc} \\
ta_{ref}^{corr} &= te_{ref}^{corr} \left(\frac{p_{sfc}}{p_{ref}} \right)^{-R_d/C_p}
\end{aligned} \tag{25}$$

6. At the end of the iterative process, obtaining diagnostics air-temperature at 2m (tas), mixing ratio at 2m (qvs) by equation 26

$$\begin{aligned}
tas &= ta_{ref}^{corr} \\
qvs &= qv_{zref}^{corr}
\end{aligned} \tag{26}$$

7. repeat 4 and 5, but for diagnostic at 10 m to obtain wind speed at 10 m (wss) as well as air-temperature $tas10$ and mixing ratio $qvz10$

Equations are also corrected after [Beljaars \(1992\)](#) and [Miller et al. \(1992\)](#).

Results from the collective and collaborative workshop, 'Atelier TKE (ATKE)' with the presence of LMDZ developing team with K. Arjdal, L. Raillard, C. Dehondt, P. Tiengou, A. Spiga, F. Cheruy, T Dubos, M. Coulon-Decorzens, S. Fromang, G. Riviere, A. Sima, F. Hourdin, E. Vignon are also considered. As a result of the workshop a new routine that computes turbulent Km / Kh coefficients with a 1.5 order closure scheme (TKE) with or without stationarity assumption (for dry atmosphere and horizontal homogeneity) was elaborated and implemented in LMDZ model.

2.5.2 Implementation in the module

Following LMDZ atmospheric model, we need at the same time, to make sure that the diagnostics are computed using as much possible the actual values of the variables simulated by the model. Since WRF-ARW computes its own drag coefficients of momentum (\mathcal{C}_m) and latent/sensible heat (\mathcal{C}_h), we must use them.

Here, code from an old version of LMDZ is used. The main subroutine in `phys/module_diagvar_cordex.F` is `SFCDIAGS_ORCHIDEE1D`

1. The * variables Θ^* (temperature) and Q^* (humidity) are computed by the equations 27 and 28

$$\Theta^* = \frac{\mathcal{C}_h \delta_z t w_{ss}|_{k=1}}{u^*} \quad (27)$$

$$Q^* = \frac{\mathcal{C}_h \delta_z q w_{ss}|_{k=1}}{u^*} \quad (28)$$

where $\delta_z t = \theta|_{k=1} - t_{sfc}$: potential temperature difference between first model level ($\theta|_{k=1} = ta|_{k=1} (p_{sfc}/p|_{k=1})^{R_d/C_p}$) and surface (t_{sfc}), $\delta_z q = \max(q|_{k=1}, 0) - \max(q_{sfc}, 0)$, correcting $\delta_z t = \text{sign}(\max(\text{abs}(\delta_z t), 1.e - 10), \delta_z t)$, $w_{ss}|_{k=1}$: wind speed at the first model level

2. The first guess of the Δ are computed at $z_{ref} = 2$ m; Δw_{ss} , $\Delta\Theta$, ΔQ (from 29 to 31, obtained using subroutine `screenc1D`)

$$\Delta w_{ss} = \begin{cases} \text{unstable } (\mathcal{L}_0 \geq 0) & \begin{cases} \frac{u^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z_0} + 1 \right) + \min \left(5, 5 \frac{z_{ref} - z_0}{\mathcal{L}_0} \right) \right] & w_{ss} > 1.5 \ \& \ \mathcal{L}_0 < 1 \ \& \ z_0 \leq 1 \\ 0.1 w_{ss} & \text{otherwise} \end{cases} \\ \text{stable} & \begin{cases} \frac{u^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z_0} + 1 \right) - 2 \ln (0.5(1 + x_{tmp})) + \right. \\ \quad 2 \ln (0.5(1 + x_{tmp0})) - \\ \quad \ln (0.5(1 + x_{tmp}^2)) + \ln (0.5(1 + x_{tmp0}^2)) + \\ \quad \left. 2 \arctan(x_{tmp}) - 2 \arctan(x_{tmp0}) \right] & w_{ss} > 5.0 \ \& \ \text{abs}(\mathcal{L}_0) \leq 50.0 \\ 0.5 w_{ss} & \text{otherwise} \end{cases} \end{cases} \quad (29)$$

$$\Delta\Theta = \begin{cases} \text{unstable } (\mathcal{L}_0 \geq 0) & \begin{cases} \frac{\Theta^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z_0} + 1 \right) + \min \left(5, 5 \frac{z_{ref} - z_0}{\mathcal{L}_0} \right) \right] & w_{ss} > 1.5 \ \& \ \mathcal{L}_0 < 1 \ \& \ z_0 \leq 1 \\ 0.1 (\theta_{air} - \theta_s) & \text{otherwise} \end{cases} \\ \text{stable} & \begin{cases} x_{tmp} = (1 - 16(z_{ref}/\mathcal{L}_0))^{1/4} \\ x_{tmp0} = (1 - 16(z_0/\mathcal{L}_0))^{1/4} \\ \frac{\Theta^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z_0} + 1 \right) - 2 \ln (0.5(1 + x_{tmp})) + \right. \\ \quad \left. 2 \ln (0.5(1 + x_{tmp0}^2)) \right] & w_{ss} > 5.0 \ \& \ \text{abs}(\mathcal{L}_0) \leq 50.0 \\ 0.5 (\Theta_{air} - \Theta_s) & \text{otherwise} \end{cases} \end{cases} \quad (30)$$

$$\Delta Q = \begin{cases} \text{unstable } (\mathcal{L}_0 \geq 0) & \begin{cases} \frac{Q^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z_0} + 1 \right) + \min \left(5, 5 \frac{z_{ref} - z_0}{\mathcal{L}_0} \right) \right] & w_{ss} > 1.5 \ \& \ \mathcal{L}_0 < 1 \ \& \ z_0 \leq 1 \\ 0.1 [\max(Q_{air}, 0) - \max(Q_{surf}, 0)] & \text{otherwise} \end{cases} \\ \text{stable} & \begin{cases} \frac{Q^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z_0} + 1 \right) - 2 \ln (0.5(1 + x_{tmp})) + \right. \\ \quad \left. 2 \ln (0.5(1 + x_{tmp0}^2)) \right] & w_{ss} > 5.0 \ \& \ \text{abs}(\mathcal{L}_0) \leq 50.0 \\ 0.5 [\max(Q_{air}, 0) - \max(Q_{surf}, 0)] & \text{otherwise} \end{cases} \end{cases} \quad (31)$$

where w_{ss} : wind speed at 1st atmospheric model level, Θ_{air} : air temperature at first model level, Q_{air} : specific humidity at first model level, Θ_s : surface air temperature (*tsk*), Q_{surf} : surface specific humidity, z_0 : rugosity, \mathcal{L}_0 : Monin-Obukov length, u^* : scale factor for the wind, Θ^* : scale factor for the potential temperature, Q^* : scale factor for the humidity, z_{ref} : reference height, Δw_{ss} : wind anomaly respect the first model level, $\Delta\Theta$: potential temperature anomaly respect the surface, ΔQ : humidity anomaly respect the surface.

3. Using them, a first guess is computed at the reference height ($z_{ref} = 2$) as by equations from 32 to 35

$$w_{ss_{z_{ref}}} = \Delta w_{ss} \quad (32)$$

$$q_{z_{ref}} = \max(q_{surf}, 0) + \Delta Q \quad (33)$$

$$\Theta_{z_{ref}} = t_{sfc} + \Delta \Theta \quad (34)$$

$$ta_{z_{ref}} = \Theta_{z_{ref}} \left(\frac{p_{sfc}}{p|_{k=1}} \right)^{-R_d/C_p} \quad (35)$$

4. Iterate to get corrected values by recomputing the coefficients (C_m, C_h) at the new reference values (χ_{ref} , using subroutine `coefcdrag1D`), applying slight corrections to the computed terms as it is shown in equations 37 to 39. In the CDXWRF implementation this is unnecessary, since, we will not get new drag coefficients, since any of the them changes during the diagnostics in order to keep the same values as the ones provided by WRF and being consistent with what the model simulates.

$$C'_m, C'_h, C'_{neutral}, R'_i, p'_{ref} = \text{coefcdrag1D}() \quad (36)$$

$$\Delta^{corr} w_{ss} = \frac{u^*}{\sqrt{C'_m}} \quad (37)$$

$$\Delta^{corr} \Theta = \Theta^* \frac{\sqrt{C'_m}}{C'_h} \quad (38)$$

$$\Delta^{corr} Q = Q^* \frac{\sqrt{C'_m}}{C'_h} \quad (39)$$

where C'_m : corrected drag coefficient for momentum, C'_h : corrected drag coefficient for sensible and latent heat at ($\chi_{z_{ref}}$). Accordingly to the consistency with WRF drag and Richardson number values, subroutine `coefcdrag1D` is modified and only provides updated R'_i and p'_{ref} , therefore $C'_m = C_m^{wrf}$, $C'_h = C_h^{wrf}$ and the Δ are the same as the ones computed at the reference level z_{ref} ; $\Delta^{corr} w_{ss} = \Delta w_{ss}$, $\Delta^{corr} \Theta = \Delta \Theta$ and $\Delta^{corr} Q = \Delta Q$

In order to obtain the pressure p_{ref} at the reference level (z_{ref}), de equation 40 is used

$$p_{ref} = \exp \left[\ln(p_{sfc}) - \frac{zg|_{k=1}}{R_d ta|_{k=1} (1 + p_{608} \max(q|_{k=1}, 0))} \right] \quad (40)$$

where p_{sfc} : surface pressure, $zg|_{k=1}$: geopotential height at the first level of the model, $ta|_{k=1}$: air temperature at the first level of the model, $q|_{k=1}$: air humidity at the first level of the model, $p_{608} = R_v/R_d - 1$

5. The new corrected values become 41 to 44

$$w_{ss}'_{z_{ref}} = \Delta^{corr} w_{ss} \quad (41)$$

$$Q'_{z_{ref}} = \Delta^{corr} Q + \max(q_{sfc}, 0) \quad (42)$$

$$\Theta'_{z_{ref}} = \Delta^{corr} \Theta + ta|_{k=1} \quad (43)$$

$$ta' = \Theta_{z_{ref}} (p_{sfc}/p_{ref})^{-R_d/C_p} \quad (44)$$

6. After 2 iterations (steps 4 and 5), the final diagnosed values become 45 and 46

$$t_{2m} = ta' \quad (45)$$

$$q_{2m} = Q'_{z_{ref}}$$

$$q_s = \frac{pq_0}{p_0} \exp \left(\frac{a_2 (t_{2m} - a_3)}{t_{2m} - a_4} \right)$$

$$q_{2m} = \min(q_s, q_{2m}) \quad (46)$$

where $a_2 = 17.2693882$, $a_3 = 273.16$ and $a_4 = 35.86$

So in summary, in CDXWRF module, implementation of diagnostics of tas and hurs at 2 m following (Hess et al., 1995) methodology, does not applies any correction-iterative method and only uses the first guess (see comparison with standard WRF values in figure 5 Code is inherited from (PhD thesis of Stéfannon, 2012) and for legacy, it will be kept in this way.

WRF does not provide the momentum surface exchange coefficient, so, a generic definition of it (shown in equation 47 Garratt, 1992) is used which was already introduced in the v1.3 of the WRF-CORDEX module.

$$Cd_m = \frac{(u^*)^2}{uas^2 + vas^2} \quad (47)$$

In order to avoid non consistent values, diagnosed values t_{2m} , q_{sm} are constrained within the surface values t_{sfc} , qv_{sfc} and model's first layer values $ta|_{k=1}$, $qv|_{k=1}$ following the equations at 48

$$\begin{cases} tamin = \min(t_{sfc}, ta|_{k=1}) \\ qvmin = \min(qv_{sfc}, qv|_{k=1}) \\ tamax = \max(t_{sfc}, ta|_{k=1}) \\ qvmax = \max(qv_{sfc}, qv|_{k=1}) \end{cases} \quad (48)$$

$$\begin{aligned} t_{2m} < tamin &\rightarrow t_{2m} = tamin \\ q_{2m} < qvmin &\rightarrow q_{2m} = qvmin \\ t_{2m} > tamax &\rightarrow t_{2m} = tamax \\ q_{2m} < qvmax &\rightarrow q_{2m} = qvmax \end{aligned}$$

2.6 tws

Wet-bulb temperature corresponds to the temperature that would have the air if saturated. This is used in surface stations in order to determine the humidity of the surface. It is also of importance for well being, since it provides a good estimate of the physical stress induced for high temperature and humidity (Raymond et al., 2020; Vecellio et al., 2022). This variable is activated with the pre-compilation flag `-DCDXWRF=2`

In this implementation is done from the work of Stull (2011). With relative humidity and temperature, the wet-bulb temperature is derived as it is shown in equation 49.

$$\begin{aligned} tws = & \quad tas \tan^{-1} \left(0.151977 \sqrt{hur + 8.313659} \right) + \tan^{-1}(tas + hurs) - \\ & \quad \tan^{-1}(hurs - 1.676331) + 0.00391838 (hurs)^{1.5} \tan^{-1}(0.023101hurs) - 4.686035 \end{aligned} \quad (49)$$

where tas : 2-m temperature, $hurs$: 2-m relative humidity.

3 new variables are added to the output:

- TWSMIN: minimum surface wet-bulb temperature, K
- TWSMAX: maximum surface wet-bulb temperature, K
- TWSMEAN: mean surface wet-bulb temperature, K

2.7 qc_pl, qr_pl, qs_pl, qi_pl, qg_pl, qh_pl

WRF directly interpolates to pressure level values during model integration including water vapour mixing ratio. In this version, the interpolation of the rest of main water species have been included (qc: cloud, qr: rain, qs: snow, qi: ice, qg: graupel and qh: hail). This is automatically added when compiling the module.

5 new variables are added to the `wrfpress (auxhist23)` output.

- QC_PL: Pressure level data, cloud mixing ratio, $kgkg^{-1}$
- QR_PL: Pressure level data, rain mixing ratio, $kgkg^{-1}$
- QS_PL: Pressure level data, snow mixing ratio, $kgkg^{-1}$
- QI_PL: Pressure level data, ice mixing ratio, $kgkg^{-1}$
- QG_PL: Pressure level data, graupel mixing ratio, $kgkg^{-1}$
- QH_PL: Pressure level data, hail mixing ratio, $kgkg^{-1}$

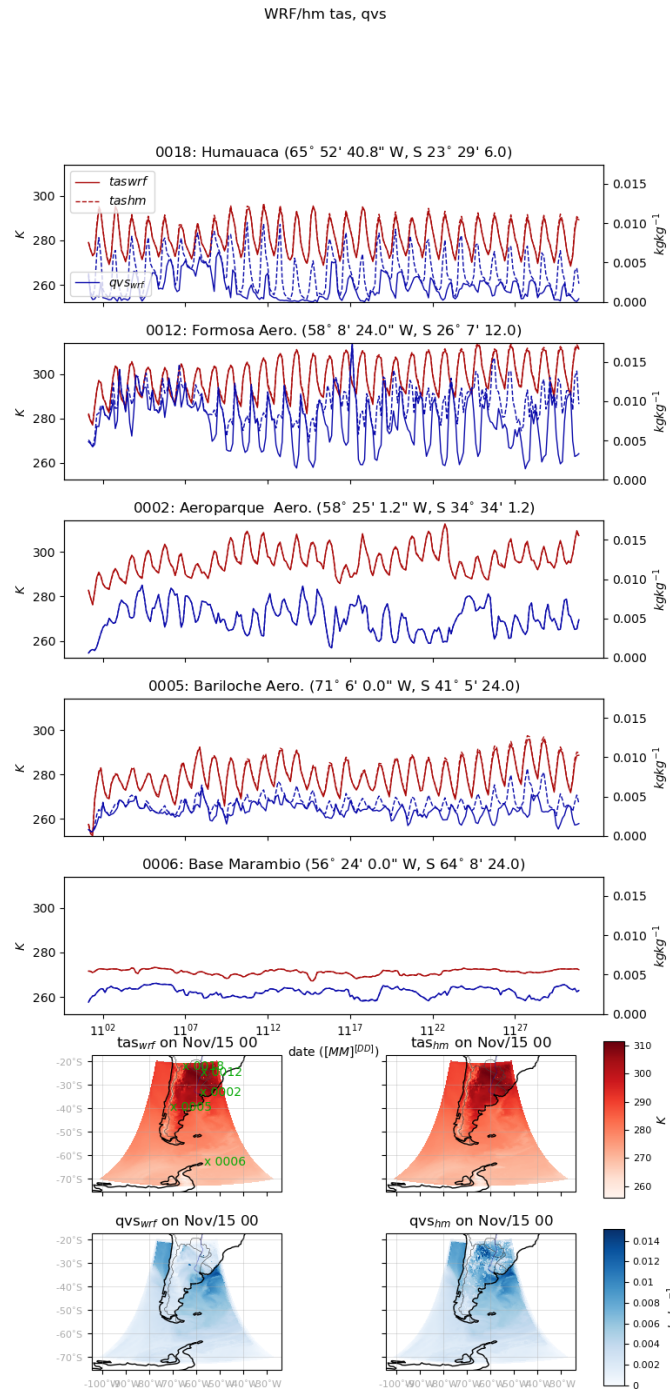


Figure 5: 2018 November 3-hourly evolution of WRF's 2-m air temperature (tas_{wrf}) and vapour mixing ratio (qvs_{wrf}) and LMDZ-based tas_{hm} , qvs_{hm} at different locations. Values of 2-m air temperature and vapour mixing ratio on 2011 November 15th at 00 UTC all over the domain

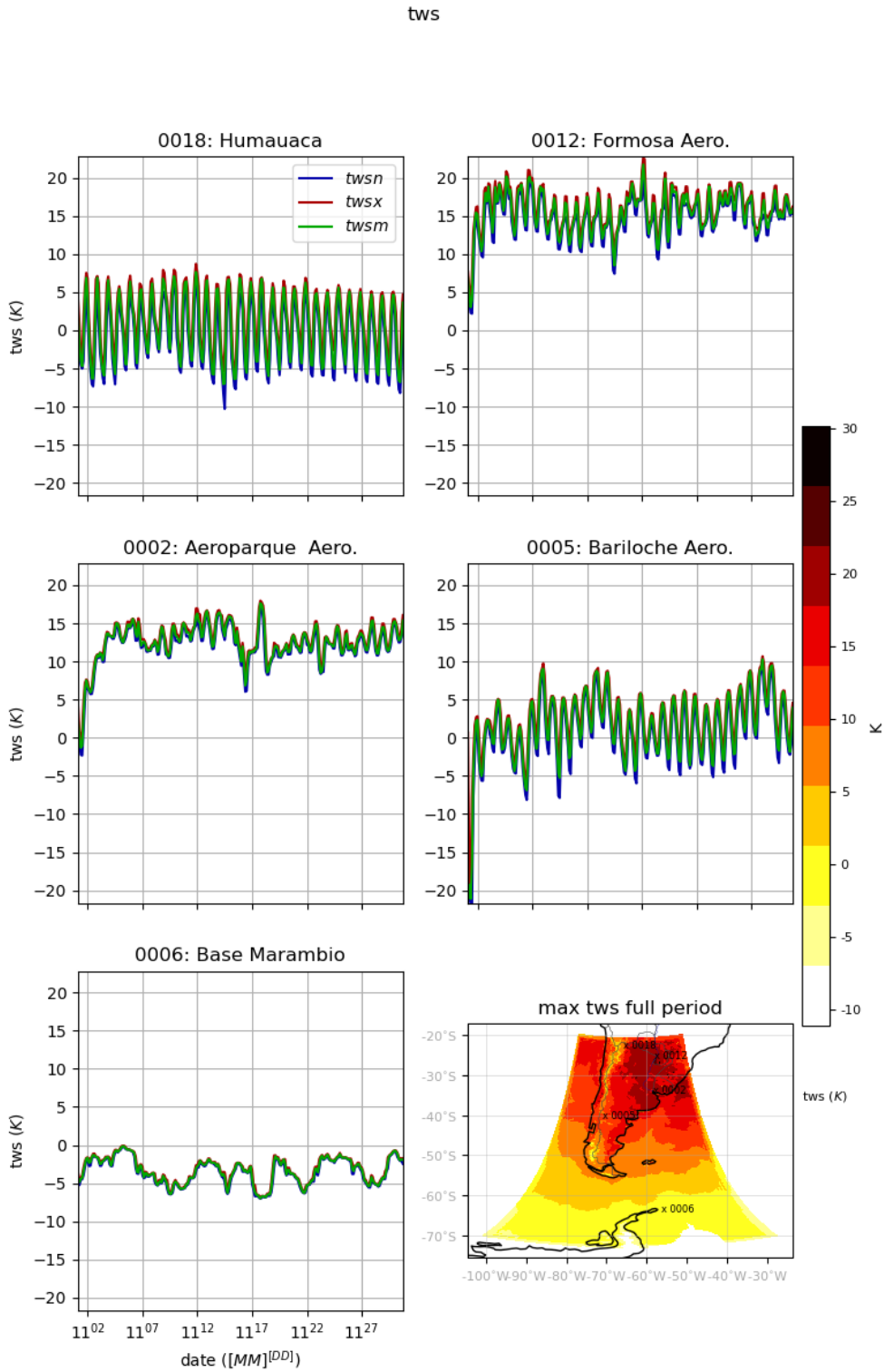


Figure 6: wet-bulb diagnostic evolution at 5 different weather stations and the maximum of tws during the period of simulation

2.8 fixing convection diagnostics

Previous version was using AFWA diagnostics from WRF v3.7.1 to diagnose convection related indices: CAPE, CIN, ZLFC, PLFC, LI. In this version, a more updated version of the diagnostics (v4.3.1) has been used, since it corrects some mistakes in the diagnostics (thanks to Zhixiao)

2.9 x_pl_mc

Currently vertical interpolation of water species to various pressure-levels is done by simple linear interpolation using the closest levels of the model. However, this induces a serious problem related to the lack of conservation of mass. Total amount of water in the column is not conserved when compared with the amount of water in the vertical of the model and the values interpolated at pressure-levels.

Here a methodology to preserve water in the column is introduced. The idea is to preserve the amount of water in the column (the mass) in a similar way as it is done when re-project surface variables such as precipitation or surface fluxes from the original projection used by the model to a new one.

This option is activated when compiling the module. It uses the same vertical pressure levels configuration as the one set-up for the standard vertical interpolation.

6 new variables are added to the wrfpress (`auxhist23`) output.

- QV_PL_MC: mass-conservative pressure level data, water vapour mixing ratio, $kgkg^{-1}$
- QC_PL_MC: mass-conservative pressure level data, cloud mixing ratio, $kgkg^{-1}$
- QR_PL_MC: mass-conservative pressure level data, rain mixing ratio, $kgkg^{-1}$
- QS_PL_MC: mass-conservative pressure level data, snow mixing ratio, $kgkg^{-1}$
- QI_PL_MC: mass-conservative pressure level data, ice mixing ratio, $kgkg^{-1}$
- QG_PL_MC: mass-conservative pressure level data, graupel mixing ratio, $kgkg^{-1}$
- QH_PL_MC: mass-conservative pressure level data, hail mixing ratio, $kgkg^{-1}$

In the vertical, due to the vertical discretization imposed in the model, mixing ratios of any water specie are constant within each of the grid cells. Each individual cell has a base and a top in the vertical dimension. When interpolating to a new fixed set of pressure-levels, we can consider them as a new discretization of the vertical axis (usually to a coarse resolution). These new cells, will have also an extension in the vertical with a bottom and a top. It is desired that the total amount of mass ($totmass_\chi$) of the water specie (χ) is preserved when vertically integrated using the model levels (p_{mod}) and the new desired p-levels (p_{des}), as it is shown in equation 50.

$$totmass_\chi = \sum_{ko=1}^{N_{mod}} mass_\chi(ko) = \sum_{kd=1}^{N_{des}} mass_\chi(kd) \quad (50)$$

where χ : water vapour, cloud, rain, snow, ice, graupel and ice, $mass_\chi(k)$: mass of the water specie χ at the k -level, ko : original vertical index in the model, kd : new desired vertical index to interpolate, N_{mod} : amount of vertical levels in the model, N_{des} : amount of desired p-level vertical levels.

Bearing in mind that water content is constant within the column, the idea is to interpolate to the 'new vertical discretization' aggregating all the water content which lays within the new grid cell (as is schematically described in equation 51)

$$mass_{chi}(kd) = \sum_{ko=koin_1}^{koin_N} mass_{chi}(koin)\delta z(koin) \quad (51)$$

where $koin_1$, $koin_N$: model vertical levels within the 'new' vertical level, $\delta z(koin)$, height of the k -model level within the 'new' vertical level.

In order to mass-conservative vertically interpolate, we follow the next steps:

1. In order to make the interpolation, the mixing ratios of the water species $q\chi$ (in $kgkg^{-1}$), are transformed to densities $\rho\chi$ (in kgm^{-3}) using the density of the dry air (ρ_{dry}) as it is shown in equation ??

$$\rho\chi = \frac{q\chi}{\rho_{dry}} \quad (52)$$

2. Define vertical extent of the grid cells.

- Original levels of the model:

- (a) WRF's geopotential height (zg in m^2s^{-2}) is vertically staggered, therefore, there is already a value at the bottom and top of each grid cell. Actual extent of the grid cells ($obthgt$, original bottom-top height, in m) which is dynamic (since WRF is no-hydrostatic) will be computed as it is shown in equation 53

$$obthgt(ko) = \begin{cases} hgt_{bot}(ko) = zg(ko)/g \\ hgt_{top}(ko) = zg(ko + 1)/g \end{cases} \quad (53)$$

where g : gravity ($9.81 ms^{-2}$)

- (b) Height at the center of the grid cell ($ohgt$, in m) will be defined as the average of the height at the bottom and top (see eq. 54)

$$ohgt(ko) = 0.5 (obthgt(ko) + obthgt(ko + 1)) \quad (54)$$

- Desired pressure levels:

- (a) There is a list of desired pressure levels at which we want to interpolate ($presdes$). The vertical extent of these grid cells ($btpresdes$, in Pa) will be defined as the mid-point between desired pressure levels. Being the surface pressure ($psfc$) the bottom limit and the pressure at the top of the model ($ptop$) the upper limit (see eq. 55). The desired pressure levels that might lay below ground ($presdes < psf$) will be filled with missing values.

$$btpresdes(kd) = \begin{cases} 0.5 (presdes(kd - 1) + presdes(kd)) \\ 0.5 (presdes(kd) + presdes(kd + 1)) \end{cases} \quad (55)$$

$$; kd = 1, btpresdes(kd) = psfc$$

$$; kd = N_{des}, btpresdes(N_{des} + 1) = ptop$$

$$(56)$$

- (b) The height of the bottom, center and top of the cells will be retrieved using the pressure ($pres$) and original model heights ($ohgt$, $obthgt$) fields of the model.

- i. Look for the 2 model's pressure nearest to the desired pressure (either for the bottom, center or top) from which one obtains $pres_{bottom}(ko')$, $pres_{top}(ko' + 1)$ (see equation 57)

$$ko'; pres(ko') \leq presdes_{bot,center,top} < pres(ko' + 1) \quad (57)$$

- ii. Using ko' and the various original model heights $ohgt/obthgt(ko')$, $ohgt/obthgt(ko' + 1)$, a linear interpolation at the $presdes_{bot,center,top}$ is used to obtain the value ($preshgt$ and $btpreshgt$, see eq. 58)

$$preshgt_{center}(kd) = \mathcal{LinInterp}[pres(ko'), pres(ko' + 1), ohgt(ko'), ohgt(ko'), pres(kd)] \quad (58)$$

$$btpreshgt(kd) = \mathcal{LinInterp}[pres(ko'), pres(ko' + 1), obthgt(ko'), obthgt(ko' + 1), btpres(kd)]$$

3. Once all the heights (center, bottom and top) have been defined for both sets (model, desired) of vertical discretizations, the mass-conservative vertical interpolation ($\rho\chi_{pl_mc}$) of the original densities ($\rho\chi$) can be done as shown in equation 59

$$\begin{aligned} valdes(kd) &= \sum_{koin=1}^{Nlev} \delta_{levorig}(ko) \rho\chi(ko) \\ &+ \delta_{levorig}^{top}(itopkin) \rho\chi(itopkin) \\ &+ \delta_{levorig}^{bot}(ibotkin) \rho\chi(ibotkin) \\ \rho\chi_{pl_mc}(kd) &= valdes(kd)/Dlevdes \end{aligned} \quad (59)$$

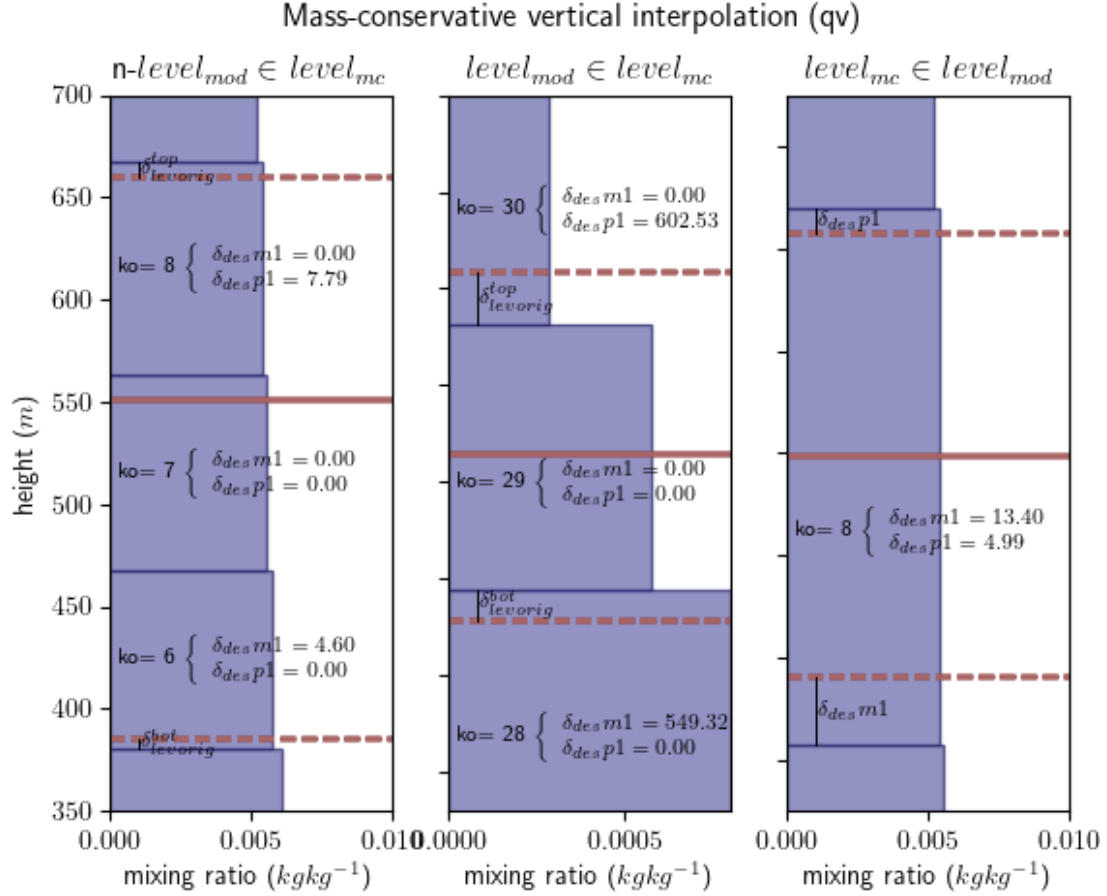


Figure 7: Schematic representation of the definition of the different values used to compute the mass at certain desired level (kd) and the respect k -level values for $\delta_{des}m1$, $\delta_{des}p1$, $\delta_{levorig}^{bot}$ and $\delta_{levorig}^{top}$. When kd encompasses multiple original model levels $ko = [6, 8]$ (left). When kd covers totally a single original model level $ko = 29$ and portions of other ones $ko = 28, 30$ (middle), When kd is within a single model level $ko = 8$ (right)

where $\rho\chi$: original model's density value, $\delta_{levorig}$: height of the original model level within the desired one (see eq. 60, $D_{levdes} = deskp1 - deskm1$: vertical extent of the desired cell, $D_{levorig} = orikp1 - orikm1$: vertical extent of the original model cell.

$$\delta_{levorig}(ko) = D_{levorig} - \delta_{des}m1 - \delta_{des}p1 \quad (60)$$

where $\delta_{des}[m/p]1$: is the vertical extent of the lower(top) section of the model's cell within the desired cell (see eq. 61 and figure 7)

$$\delta_{des}m1 = \begin{cases} deskm1 - orikm1 & deskm1 > orikm1 \\ 0 & deskm1 < orikm1 \end{cases} \quad \delta_{des}p1 = \begin{cases} orikp1 - deskp1 & deskp1 < orikp1 \\ 0 & deskp1 > orikp1 \end{cases} \quad (61)$$

where $\delta_{levorig}^{top}(itopkin)$: is the vertical extent of the top section of the model's cell within the desired cell ($ko' = itopkin$), but with model's cell center outside the desired cell range (see eq. 62)

$$\delta_{levorig}^{top}(itopkin) = orikp1 - deskm1 \quad (62)$$

where $\delta_{levorig}^{bot}(ibotkin)$: is the vertical extent of the bottom section of the model's cell within the desired cell ($ko' = ibotkin$), but with model's cell center outside the desired cell range (see eq. 63)

$$\delta_{levorig}^{bot}(ibotkin) = deskp1 - orikm1 \quad (63)$$

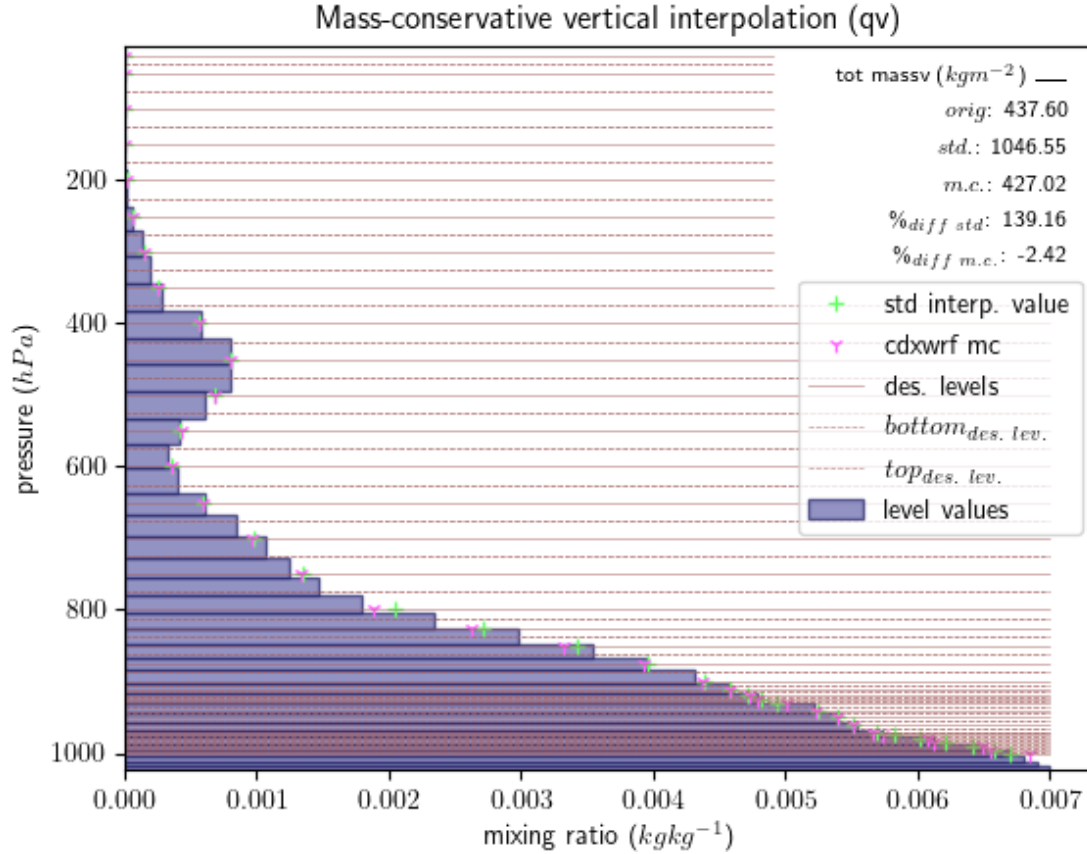


Figure 8: Validation of the mass-conservative interpolation at a given grid point for water vapour mixing ratio (qv in $kgkg^{-1}$, x-axis) for 36 vertical desired pressure levels. Color bars in pale blue are the different qv at the original model η levels (at each respective pressures, y-axis). '+' interpolation using the standard linear interpolation, 'tri-star' interpolation using the mass-conservative interpolation. Straight lines indicate the desired pressure value for the vertical interpolation. Dotted lines indicate the bottom/top of the desired vertical layers. Top right values illustrate the total column mass of water vapour (in kgm^{-2}) for each case. 'orig': original model mass, 'std': mass using standard interpolated values, 'mc': mass using the mass-conservative interpolation method. %diff std.: percentage of difference for the standard total mass with respect the one from the model, %diff m.c.: percentage of difference for the mass-conservative total mass with respect the one from the model

where $orikm1$: value at the base of the original cell ($obthgt(ko')$), $orikp1$: value at the top of the original cell ($obthgt(ko' + 1)$), $deskm1$: value at the base of the desired cell ($obtpreshgt(kd)$), $deskp1$: value at the top of the desired cell ($obtpreshgt(kd + 1)$), $Nlev$: amount of original levels within the height of the kd -desired cell ($Nlev$; $orilev(ko) \leq deskm1$ & $orilev(ko) > deskp1$)

4. Dry air density (ρ_{dry}) of the model is also mass-conservatively interpolated to the desired pressure levels to provide $\rho_{dry_pl_mc}$
5. Finally, obtained interpolated water densities at the desired pressure levels of specie $\rho_{\chi_pl_mc}$, will be transformed to mixing ratios $q_{\chi_pl_mc}$ using the interpolated dry density ρ_{dry_des} as it is shown in eq. 64 (see figure 8)

$$q_{\chi_pl_mc} = \frac{\rho_{\chi_pl_mc}}{\rho_{dry_pl_mc}} \quad (64)$$

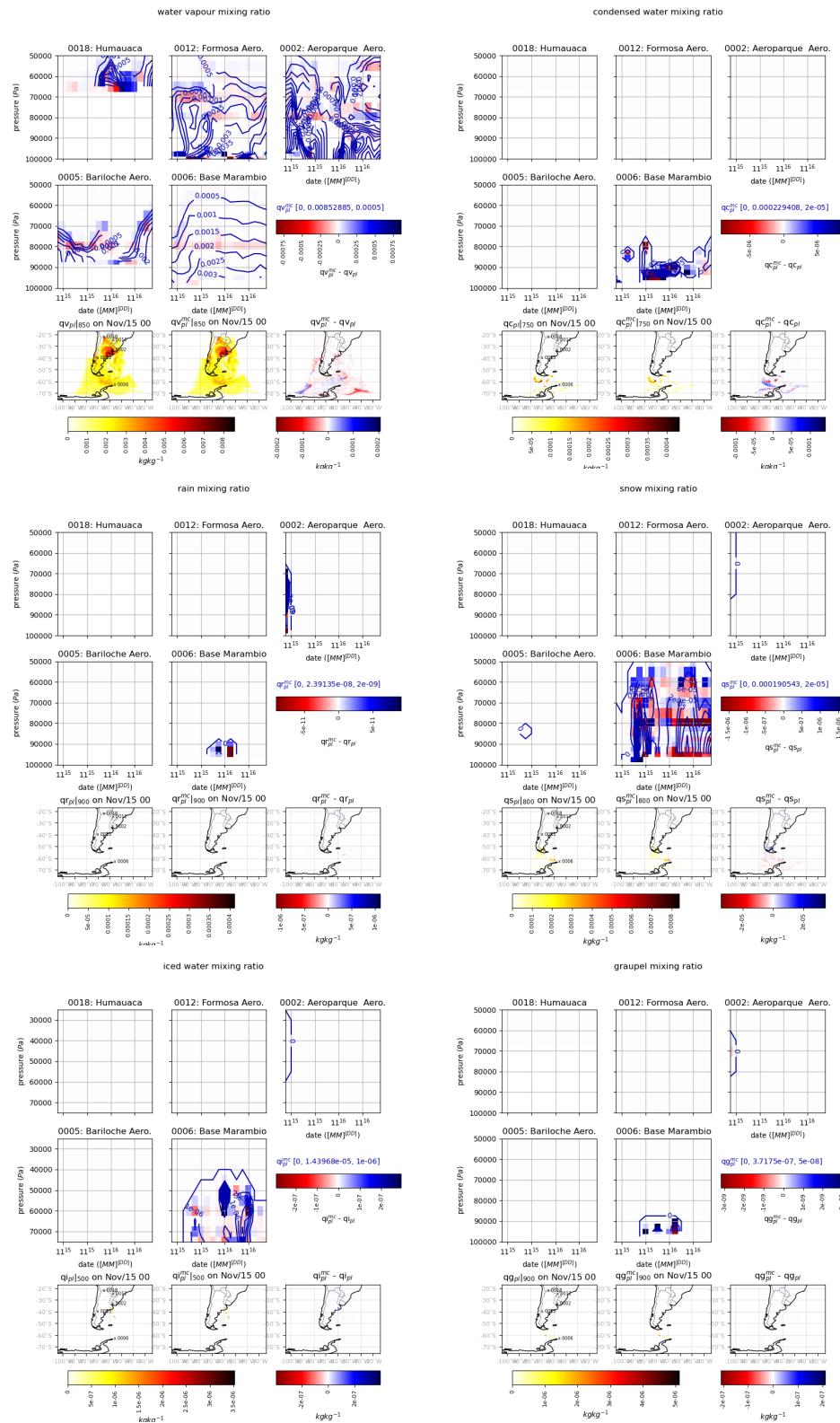


Figure 9: Differences between standard vertical interpolation ($q\chi_{pl}$) and mass-conservative ones ($q\chi_{pl}^{mc}$) over 23 pressure levels. Differences for vapour mixing ratio (q_v), cloud (q_c), rain (q_r), snow (q_s), ice (q_i) and graupel (q_g). Evolution of vertical profiles (contour in blue for mass. consev. interpolation) and differences among interpolations (shaded) at 5 different stations. Maps at a given vertical level and instant (2011 November 15th at 00 UTC) for each interpolation and the differences

2.10 simultaneous residence time

This variable aggregates the time passed (*'time of residence'*) during the integration of the model, at each grid point of the domain, where 2 different variables (in this case: 2-m temperature (tas) and humidity (hurs)) simultaneously passed at within certain range of values (2 bins). The variable will reflect the total time passed at the given location where tas values were within a given range and hurs values within another one. This variable is related to the *growing degree-day* (GDD¹) used in agriculture or pest control. It is more sophisticated, because it incorporates the simultaneity with relative humidity which has also a strong influence in the life cycle of insects (to cite some examples [Rudolfs, 1925](#); [Kingsolver et al., 2011](#); [Tamiru et al., 2012](#)). This diagnose is activated when compiling with `-DCDXWRF=3`.

The diagnose introduces 2 new variables:

- TASHURSTRESHIGHRES: high-resolution of simultaneous temporal residence of 2-m temperature and relative humidity, *second*
- TASHURSTRESLOWRES: low-resolution of simultaneous temporal residence of 2-m temperature and relative humidity, *second*

The option is set-up with 6 new parameters in the namelist:

- `nhtasrng`: amount + 1 of high-resolution bins for temporal residence of tas (default value 42)
- `nhhursrng`: amount + 1 of high-resolution bins for temporal residence of hurs (default value 23)
- `nltasrng`: amount + 1 of low-resolution bins for temporal residence of tas (default value 16)
- `nlhursrng`: amount + 1 of low-resolution bins for temporal residence of hurs (default value 23)
- `htasrng`: high-resolution bins for temporal residence of tas (default value: -5 to 35 by 1. °C)
- `hhursrng`: high-resolution bins for temporal residence of hurs (default value: 0. to 1.05 by 0.05 %)
- `ltasrng`: low-resolution bins for temporal residence of tas (default value: -25 to 45.by 5. °C)
- `lhursrng`: low-resolution bins for temporal residence of hurs (default value: 0. to 1.05 by 0.05 %)

Two different high/low times of residence are defined as a way to provide valuable information to a larger amount of communities (e.g. glaciologists, ecologists, farmers, ...) without overloading the simulation. Is understood that the *high* resolution diagnostic is focused in the 'bio/eco-logical' area, whereas *low* resolution diagnostics might be more suitable for physical analyses (e.g.: glacial melting, heat stress, ...)

The diagnose is computes as follows

1. The tas variable is discretized by a series of bins: $tas(n), tas(n+1), tas(n+2), \dots, tas(N)$
2. The hurs variable is discretized by a series of bins: $hurs(m), hurs(m+1), hurs(m+2), \dots, hurs(M)$
3. The time of residence accumulates the time passed (during the integration of the model at time-steps dt) simultaneously at each possible combination of bins for tas and hurs (see eq. 65).

$$\begin{aligned}
 simultaneous_residence_time(i, j, n+1, m+1) &= \sum_{it} dt \left\{ \begin{array}{l} tas(n) \leq tas(i, j, it) < tas(n+1) \\ hurs(m) \leq hurs(i, j, it) < hurs(m+1) \end{array} \right. \\
 simultaneous_residence_time(i, j, 1, 1) &= \sum_{it} dt \left\{ \begin{array}{l} tas(i, j, it) < tas(1) \\ hurs(i, j, it) < hurs(1) \end{array} \right. \\
 simultaneous_residence_time(i, j, N+1, M+1) &= \sum_{it} dt \left\{ \begin{array}{l} tas(i, j, it) \geq tas(N) \\ hurs(i, j, it) \geq hurs(M) \end{array} \right.
 \end{aligned} \tag{65}$$

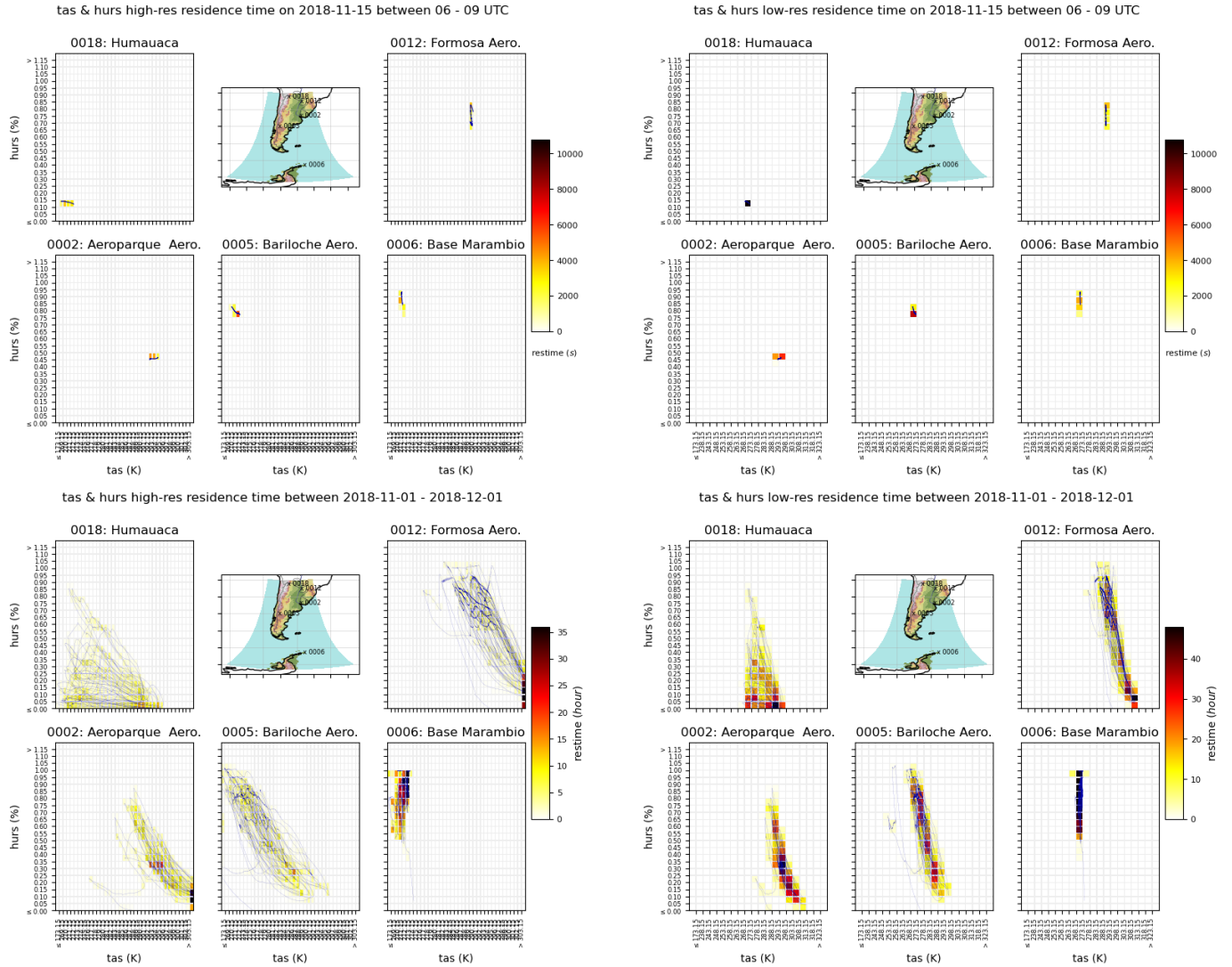


Figure 10: Example of residence time for 25 km simulation over entire Argentina and Chile at 5 different locations (see map and labels on the panels). Residence time in seconds on 2018 November 15th between . (top row). Total monthly residence time in hours for November 2018 (bottom row). For high-resolution bins (left column) for low-resolution bins (right column). Selected bins are given in equation 66

$$\left\{ \begin{array}{l}
tas_{highres} = \left[\begin{array}{l} 173.15, 268.15, 269.15, 270.15, 271.15, 272.15, 273.15, 274.15, 275.15, \\ 276.15, 277.15, 278.15, 279.15, 280.15, 281.15, 282.15, 283.15, 284.15, \\ 285.15, 286.15, 287.15, 288.15, 289.15, 290.15, 291.15, 292.15, 293.15, \\ 294.15, 295.15, 296.15, 297.15, 298.15, 299.15, 300.15, 301.15, 302.15, \\ 303.15, > 303.15 \end{array} \right] \\
hurs_{highres} = \left[\begin{array}{l} 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, \\ 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1, \\ 1.05, 1.1, 1.15, > 1.15 \end{array} \right] \\
tas_{lowres} = \left[\begin{array}{l} 173.15, 233.15, 238.15, 243.15, 248.15, 253.15, 258.15, 263.15, 268.15, \\ 273.15, 278.15, 283.15, 288.15, 293.15, 298.15, 303.15, 308.15, 313.15, \\ 318.15, 323.15, > 323.15 \end{array} \right] \\
hurs_{lowres} = hurs_{highres}
\end{array} \right. \quad (66)$$

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¹https://en.wikipedia.org/wiki/Growing_degree-day

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A LMDZ’s tas, qvs, wss

Detailed description of the new implementation of the 2-m and 10-m diagnoses in LMDZ.

A.1 cdrag_mod.F90

Subroutine `cdrag` computes differently if it is an ocean (see sub-section A.1.1) or a land point (section A.1.2).

First generic values are defined as shown in 67 (some of them are configurable from LMDZ model set-up)

$$\left\{ \begin{array}{l} C_{KAP} = 0.40; C_{KAPT} = 0.42 \\ \textit{iter. rugosity coeff.} \\ \textit{squared minimum wind} \\ \\ \textit{Louis 1982 coeff.} \\ \\ \textit{King 2001 coeff.} \\ \\ \textit{Louis 1979 coeff} \\ \\ \textit{Monin - Obukhov} \\ \\ \textit{Consistency with atke scheme} \end{array} \right. \left\{ \begin{array}{l} \textit{tol[it]}_{z_0} = 1.e^{-4} \\ CEPDU2 = (0.1)^2 \\ \left\{ \begin{array}{l} C_B = 5.0 \\ C_C = 5.0 \\ C_D = 5.0 \end{array} \right. \\ \left\{ \begin{array}{l} C_2 = 0.25 \\ C_3 = 0.0625 \end{array} \right. \\ \left\{ \begin{array}{l} BPRIME = 4.7 \\ B = 9.4 \end{array} \right. \\ \alpha = 5.0 \\ \left\{ \begin{array}{l} C_\epsilon = 5.87; C_{inf} = 1.5; R_{ic} = 0.25; \\ pr_{asym} = 0.4; pr_{neut} = 0.8; pr_{slope} = 5.0 \\ cn = \left(\frac{1}{\sqrt{C_\epsilon}} \right)^{2/3} \\ ri_0 = \frac{2}{\pi} (C_{inf} - cn) \frac{R_{ic}}{cn} \\ ri_1 = -\frac{2}{\pi} \frac{pr_{asym} - pr_{neut}}{pr_{slope}} \end{array} \right. \end{array} \right. \quad (67)$$

$$\begin{aligned} R_{i,Cd}^{min} &= 0.1 \\ C_{drag}^{ter} &= 0.8; C_{drag}^{oce} = 0.8 \\ Cd_m^{max} &= 1.3e^{-3}; Cd_h^{max} = 1.3e^{-3} \end{aligned}$$

as well as performing some consistency tests 68 to remove 0 values

$$\textit{initial tests} \left\{ \begin{array}{l} q|_{k=1} < 0 \longrightarrow q|_{k=1} = 0 \\ q_{sfc} < 0 \longrightarrow q_{sfc} = 0 \end{array} \right. \quad (68)$$

and preparing the iterative methodology 69 where at the first call, the stability functions to be used will be `iflag_corr_sta=2, iflag_corr_insta=2, ok_cdrag_iter = .FALSE.` (or passed as namelist values in LMDZ configuration)

$$\begin{aligned} z_0_m^{iter}(1,2) & \left\{ \begin{array}{l} (1) = z_0_m \quad \textit{initial value} \\ (2) = 3tol[it]_{z_0} z_0_m \quad \textit{iterative momentum value} \end{array} \right. \\ z_0_h^{iter}(1,2) & \left\{ \begin{array}{l} (1) = z_0_h \quad \textit{initial value} \\ (2) = 3tol[it]_{z_0} z_0_h \quad \textit{iterative heat value} \end{array} \right. \end{aligned} \quad (69)$$

Additional preliminary values as by 70

$$\begin{aligned}
Re_{tv} &= R_v/R_d - 1.; \quad RC_{pd} = 1/C_{pd}; \quad RC_{pv} = 4R_v \\
Rv_{tmp2} &= RC_{pv}/RC_{pd} - 1 \\
z_{du}^2 &= \max(CEPDU2, wss^2) \\
p_{ref} &= \exp \left[\ln(p_{sfc}) - \frac{zg|_{k=1}}{R_d t|_{k=1} (1 + Re_{tv} \max(qv|_{k=1}, 0))} \right] \\
zt_{sfcv} &= t_{sfc} (1 + Re_{tv} \max(q_{sfc}, 0)) \\
zt_{vd} &= \left(t|_{k=1} + \frac{zg|_{k=1}/RC_{pd}}{1 + Rv_{tmp2} qv|_{k=1}} \right) (1 + Re_{tv} \max(q|_{k=1}, 0))
\end{aligned} \tag{70}$$

A.1.1 ocean points

First the multiple coefficients are computed using `clc_core_cp` (from `libf/phyimd/clc_core_cp.F90`) as 71 with the parameters from (Smith et al., 2001; Large and Yeager, 2004; Large, 2006), mixt calculation will be accordingly to different configuration parameters

```

choix_bulk > 1 && choix_bulk < 4
choix_bulk == 2;
  mixte = .false.
else
  mixte = .true.

```

$$\begin{aligned}
Z_\chi &= zg|_{k=1}/g, \quad \chi = wss, t, q \\
\log z\chi_{10} &= \ln(z_\chi/10) \\
\log z\chi_{zu} &= \log z\chi_{10} - \log zu_{10} \\
C_{pa} &= 1004.67 \\
t_v &= ta|_{k=1} (1 + 0.608q|_{k=1}), \quad \text{virtual temperature} \\
\rho &= \frac{p_{sfc}}{287.1 ta|_{k=1} (1 + 0.61q|_{k=1})}, \quad \text{sfc. density} \\
\text{vert.gradient} &\begin{cases} \delta ta = t|_{k=1} - t_{sfc} \\ \delta qv = q|_{k=1} - q_{sfc} \end{cases} \\
L_e &= (2.501 - 0.00237(ta|_{k=1} - 273.15 - \delta ta)) 1e^6, \quad \text{latent heat} \\
wss_{first} &= \max \left(\sqrt{z_{du}^2}, 5 \right) \\
\text{Large and Yeager 2006, 2004} &\begin{cases} \alpha = 2.7e^{-3} \quad (a_1 \text{ Smith}) \\ \beta = 1.42e^{-4} \quad (a_2 \text{ Smith}) \\ \gamma = 7.64e^{-5} \quad (a_3 \text{ Smith}) \\ q_0 = 1.64474 \end{cases} \\
g &= 9.81, \quad \text{gravity}
\end{aligned} \tag{71}$$

First approximation to z_0 (rugosity), C_d (momentum coefficient, C_d^{10} at 10 m), C_h (heat coeff.) and C_e (moisture) as by 72 to 75

$$\text{First guess} \begin{cases} \text{mixte (Smith)} \\ \text{Large and Yeager 2004, 2006} \end{cases} \begin{cases} z0_m = 1e^{-4} \\ C_d^{10} = \frac{\kappa^2}{(\ln(10/z0_m))_\alpha^2} \\ C_d^{10} = \frac{1}{wss_{first} + \beta + \gamma wss_{first}} \\ z0_m = 10 \exp \left(-\kappa / \sqrt{C_d^{10}} \right) \end{cases} \tag{72}$$

$$\text{Stability} \quad \begin{cases} C_h^{10} = 0.018\sqrt{C_d^{10}} & \text{stable } (\delta ta < 0) \\ C_h^{10} = 0.0327\sqrt{C_d^{10}} & \text{(unstable)} \end{cases} \quad (73)$$

$$C_e^{10} = 3.46e^{-2}\sqrt{C_d^{10}} \quad (74)$$

$$\text{coeffs.} \quad \begin{cases} C_d = C_d^{10} \\ C_h = C_h^{10} \\ C_e = C_e^{10} \end{cases} \quad (75)$$

Computing star coefficients χ^* (for wss , ta , qv) 76 by iterations for n_it (1, default value, but configurable in LMDZ)

$$\chi^* \quad \begin{cases} u^* = wss\sqrt{C_d} \\ ta^* = \delta ta \frac{C_h}{\sqrt{C_d}} \\ qv^* = \delta qv \frac{C_e}{\sqrt{C_d}} \end{cases} \quad (76)$$

$$\text{stability} \quad \begin{cases} \mathcal{Z}(wss, ta, qv) = (z_u, z_{ta}, z_{qv}) \frac{\kappa g}{(u^*)^2} \frac{ta^*}{|k=1} \\ \mathcal{Z}(wss, ta, qv) = \min(\mathcal{Z}(wss, ta, qv), \pm 10) \end{cases} \quad (77)$$

$$\text{wind speed} \quad \begin{cases} \text{stable } (\mathcal{Z}(1) > 0) \begin{cases} \chi = 0.018 \\ \psi_a(1) = -5\mathcal{Z}(1) \\ \psi_b(1) = \psi_a(1) \end{cases} \\ \text{unstable} \begin{cases} \chi = 0.0327 \\ \mathcal{X} = \sqrt{\sqrt{1 - 16\mathcal{Z}(1)}} \\ \psi_a(1) = \frac{\pi}{2} + 2 \ln\left(\frac{1+\mathcal{X}}{2}\right) + \ln\left(\frac{1+\mathcal{X}^2}{2}\right) - 2\arctan(\mathcal{X}) \\ \psi_b(1) = 2 \ln\left(\frac{1+\mathcal{X}^2}{2}\right) \end{cases} \end{cases} \quad (78)$$

$$ta(2), qv(3) \quad \begin{cases} \text{stable } (\mathcal{Z}(j) > 0) \begin{cases} \psi_a(j) = -5\mathcal{Z}(2) \\ \psi_b(j) = \psi_a(1) \end{cases} \\ \text{unstable} \begin{cases} \mathcal{X} = \sqrt{\sqrt{1 - 16\mathcal{Z}(j)}} \\ \psi_a(j) = \frac{\pi}{2} + 2 \ln\left(\frac{1+\mathcal{X}}{2}\right) + \ln\left(\frac{1+\mathcal{X}^2}{2}\right) - 2\arctan(\mathcal{X}) \\ \psi_b(j) = 2 \ln\left(\frac{1+\mathcal{X}^2}{2}\right) \end{cases} \end{cases} \quad (79)$$

$$\delta ta_u = \delta ta - \frac{ta^*}{\kappa} (\log z_{ta_{zu}} + \psi_b(1) - \psi_b(2)) \quad (80)$$

$$\delta qv_u = \delta qv - \frac{qv^*}{\kappa} (\log z_{qv_{zu}} + \psi_b(1) - \psi_b(3)) \quad (81)$$

$$wss_N = \frac{wss_{first}}{1 + \sqrt{C_d^{10}}/\kappa (\log z_{u_{10}} - \psi_a(1))} \quad (82)$$

$$\text{coefs} \left\{ \begin{array}{l}
\text{mixte (Smith)} \left\{ \begin{array}{l}
z0_m = 0.018 \frac{(u^*)^2}{\kappa^2 g} + \frac{0.11 \times 14e^{-6}}{u^*} \\
C_d^{10} = \frac{g}{(\ln(10/z0_m))^2} \\
C_h^{10} = 1e^{-3}
\end{array} \right. \\
\text{Large and Yaeger2004, 2006} \left\{ \begin{array}{l}
C_d^{10} = \frac{\alpha}{wss_N} + \beta + \gamma wss_N \\
z0_m = 10 \exp\left(-\kappa/\sqrt{C_d^{10}}\right) \\
C_h^{10} = \chi \sqrt{C_d^{10}}
\end{array} \right. \\
C_e^{10} = 3.46e^{-2} \sqrt{C_d^{10}} \\
\phi_d = 1 + \frac{\sqrt{C_d^{10}}}{\kappa} (\log zu_{10} - \psi_a(1)) \\
\phi_h = 1 + \frac{\chi}{\kappa} (\log zu_{10} - \psi_b(1)) \\
\phi_e = 1 + \frac{3.46e^{-2}}{\kappa} (\log zu_{10} - \psi_b(1)) \\
C_d = \left(\frac{\sqrt{C_d^{10}}}{\text{abs}(\phi_d)} \right)^2 \\
C_h = \frac{C_h^{10}}{\phi_h \phi_d} \\
C_e = \frac{C_e^{10}}{\phi_e \phi_d}
\end{array} \right. \quad (83)$$

Coefficients are finally computed as 84 to 86

$$u^* = wss_{first} \sqrt{C_d} \quad (84)$$

$$ta^* = \delta ta_u \frac{C_h}{\sqrt{C_d}} \quad (85)$$

$$qv^* = \delta qv_u \frac{C_e}{\sqrt{C_d}} \quad (86)$$

To obtain the coefficients over sea, different methodologies are used:

- `choix_bulk = 4`: ECUME parametrization (Belamari, 2005; Belamari et al., 2016) and other modifications
- `choix_bulk = 5`: bulk algorithm COARE3.0 (Fairall et al., 2003) and subsequent modifications
- `choix_bulk = 1`: simplified version of the bulk algorithm COARE performed by LMDZ developers
- `default LMDZ`: $R_i = zg|_{k=1} \frac{zt_{vd} - zt_{sfv}}{z_{du}^2 zt_{vd}}$

Then the neutral coefficients are obtained:

$$\begin{aligned}
C_d^{neut} &= \frac{C_{KAP}}{\ln(1 + zg|_{k=1}/(gz0_m^{iter}(2)))} \\
C_{dm}^{neut} &= (C_d^{neut})^2 \\
C_{dh}^{neut} &= C_d^{neut} \left(\frac{C_{KAP}}{\ln(1 + zg|_{k=1}/(gz0_h^{iter}(2)))} \right)
\end{aligned} \quad (87)$$

the vertical profiles can be computed as in 88 ($R_i < 0$, unstable, selecting by `iflag_corr_insta`) and 90 ($R_i > 0$, stable, selecting via `iflag_corr_sta`) following an iterative method by `nit_bulk` (1, by default but adjustable in

LMDZ)

$$\begin{aligned}
& \left\{ \begin{array}{l} \mu = \ln(\max(z_{0m}/z_{0h}, 0.01)) \\ CM^* = 6.8741 + 2.6933\mu - 0.3601\mu^2 + 0.0154\mu^3 \\ \mathcal{P}_m = 0.5233 - 0.0815\mu + 0.0135\mu^2 - 0.001\mu^3 \\ CH^* = 3.2165 + 4.3431\mu + 0.536\mu^2 - 0.0781\mu^3 \\ \mathcal{P}_h = 0.5802 - 0.1571\mu + 0.0327\mu^2 - 0.0026\mu^3 \\ C_h = \frac{CH^* BC_{KAP}}{\ln(z_{0m} + zg|_{k=1}/(gz_{0m}))} \frac{C_{KAPT}}{\ln(z_{0h} + zg|_{k=1}/(gz_{0h}))} \left(\frac{zg|_{k=1}}{gz_{0h}} \right)^{\mathcal{P}_h} \\ C_m = \frac{CM^* BC_{KAP}}{\ln(z_{0m} + zg|_{k=1}/(gz_{0m}))} \frac{C_{KAP}}{\ln(z_{0m} + zg|_{k=1}/(gz_{0m}))} \left(\frac{zg|_{k=1}}{gz_{0m}} \right)^{\mathcal{P}_m} \\ \mathcal{F}_m = 1 - \frac{BR_i}{1 + C_m \sqrt{ABS(R_i)}} \\ \mathcal{F}_h = 1 - \frac{BR_i}{1 + C_h \sqrt{ABS(R_i)}} \end{array} \right. \quad (88) \\
& \text{Louis 1982 (2)} \quad \left\{ \begin{array}{l} zu_{cf} = \frac{1}{1 + 3C_B C_C C_{dm}^{neut} \sqrt{abs(R_i)(1 + zg|_{k=1}/(gz_{0m}))}} \\ \mathcal{F}_m = \max\left(1 - 2C_B R_i zu_{cf}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left(1 - 3C_B R_i zu_{cf}, R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{Laurent Li (3)} \quad \left\{ \begin{array}{l} \mathcal{F}_m = \max\left(\sqrt{1 - 18R_i}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left(\sqrt{1 - 18R_i}, R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{After ATKE (6)} \quad \left\{ \begin{array}{l} s_m = \frac{2}{\pi}(C_{inf} - cn)\arctan(-R_i/r_{i0}) + cn \\ prandtl = -\frac{2}{\pi}(pr_{asym} - pr_{neut})\arctan(R_i/r_{i1}) + pr_{neut} \\ \mathcal{F}_m = \max\left(s_m^{3/2} \sqrt{C_\epsilon} (1 - R_i/prandtl)^{1/2}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left(\mathcal{F}_m/prandtl, R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{default (Louis 1982)} \quad \left\{ \begin{array}{l} zu_{cf} = \frac{1}{1 + 3C_B C_C C_{dm}^{neut} \sqrt{abs(R_i)(1 + zg|_{k=1}/(gz_{0m}))}} \\ \mathcal{F}_m = \max\left(1 - 2C_B R_i zu_{cf}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left(1 - 3C_B R_i zu_{cf}, R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{drag coeff.} \quad \left\{ \begin{array}{l} Cd_m = C_d^{neut} \mathcal{F}_m \\ Cd_h = C_{drag}^{ter} C_d^{neut} \mathcal{F}_h \\ \text{without gustiness} \left\{ \begin{array}{l} z_{cr} = \frac{0.0016}{C_{dm}^{neut} \sqrt{z_{du}^2}} abs(z_{tvd} - z_{tsfcv})^{1/3} \\ Cd_h = C_{drag}^{oce} C_{dh}^{neut} (1 + z_{cr}^{1.25})^{1/1.25} \end{array} \right. \\ Cd_m = \min(Cd_m, Cd_m^{max}) \\ Cd_h = \min(Cd_h, Cd_h^{max}) \end{array} \right. \quad (89)
\end{aligned}$$

For the stable cases previously one applies $R_i = \min(20, R_i)$

$$\begin{aligned}
& \text{Louis 1979 \& Mascart 1995 (1)} \quad \left\{ \begin{array}{l} \mathcal{F}_m = \max\left(\frac{1}{(1 + BPRIME R_i)^2}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \quad (90) \\
& \text{Louis 1982 (2)} \quad \left\{ \begin{array}{l} zs_{cf} = \sqrt{1 + C_D abs(R_i)} \\ \mathcal{F}_m = \max\left(\frac{1}{1 + 2C_B R_i / zs_{cf}}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left(\frac{1}{1 + 3C_B R_i / zs_{cf}}, R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{Laurent Li (3)} \quad \left\{ \begin{array}{l} \mathcal{F}_m = \max\left(\frac{1}{1 + 10R_i(1 + 8R_i)}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \\
& \text{King 2001 (4)} \quad \left\{ \begin{array}{l} R_i < C_2/2 \left\{ \begin{array}{l} \mathcal{F}_m = \max\left((1 - R_i/C_2)^2, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \\ \left\{ \begin{array}{l} \mathcal{F}_m = \max\left(C_3(C_2/R_i)^2, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \end{array} \right.
\end{aligned}$$

$$\begin{aligned}
\text{Monin - Obukhov (5)} & \left\{ \begin{array}{l} R_i < 1/\alpha \left\{ \begin{array}{l} \mathcal{F}_m = \max \left((1 - \alpha R_i)^2, R_{i,Cd}^{min} \right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \\ \left\{ \begin{array}{l} \mathcal{F}_m = \max \left(1e-7, R_{i,Cd}^{min} \right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \end{array} \right. \\
\text{After ATKE (6)} & \left\{ \begin{array}{l} s_m = \max(0, cn(1 - R_i/R_{ic})) \\ prandtl = pr_{neut} + R_i pr_{slope} \\ \mathcal{F}_m = \max \left(s_m^{3/2} \sqrt{C_\epsilon} (1 - R_i/prandtl)^{1/2}, R_{i,Cd}^{min} \right) \\ \mathcal{F}_h = \max \left(\mathcal{F}_m/prandtl, R_{i,Cd}^{min} \right) \end{array} \right. \\
\text{Louis 1982 (default)} & \left\{ \begin{array}{l} z_{s_{cf}} = \sqrt{1 + C_{Dabs}(R_i)} \\ \mathcal{F}_m = \max \left(\frac{1}{1+2C_B R_i/z_{s_{cf}}}, R_{i,Cd}^{min} \right) \\ \mathcal{F}_h = \max \left(\frac{1}{1+3C_B R_i/z_{s_{cf}}}, R_{i,Cd}^{min} \right) \end{array} \right. \\
\text{drag coeff.} & \left\{ \begin{array}{l} Cd_m = Cd_m^{neut} \mathcal{F}_m \\ Cd_h = C_{drag}^{ter} Cd_h^{neut} \mathcal{F}_h \end{array} \right. \quad (91) \\
\text{choix_bulk} = 0 & \left\{ \begin{array}{l} Cd_m = Cd_m^{neut} \mathcal{F}_m \\ Cd_h = C_{drag}^{ter} Cd_h^{neut} \mathcal{F}_h \end{array} \right. \quad (92) \\
\text{ocean points} & \left\{ \begin{array}{l} Cd_h = C_{drag}^{oce} Cd_h^{neut} \mathcal{F}_h \\ Cd_m = \min(Cd_m, Cd_m^{max}) \\ Cd_h = \min(Cd_h, Cd_h^{max}) \end{array} \right. \quad (93) \\
\text{whilst iterating} & \left\{ \begin{array}{l} z0_m^{iter}(1) = z0_m^{iter}(2) \\ z0_h^{iter}(1) = z0_h^{iter}(2) \\ z0_m^{iter}(2) = 0.018 * Cd_m \frac{wss}{g} + 0.11 \frac{14e^{-6}}{\sqrt{Cd_m z_{du}^2}} \\ \text{differentiate } z0 \left\{ \begin{array}{l} z0_h^{iter}(2) = z0_m^{iter}(2) \\ z0_h^{iter}(2) = 0.40 \frac{14e^{-6}}{\sqrt{Cd_m z_{du}^2}} \\ z0_m^{iter}(2) = \max(1.5e^{-05}, z0_m^{iter}(2)) \\ z0_h^{iter}(2) = \max(1.5e^{-05}, z0_h^{iter}(2)) \end{array} \right. \end{array} \right. \quad \begin{array}{l} iflag_z0_oce = 0 \\ iflag_z0_oce = 1 \end{array} \quad (94)
\end{aligned}$$

For which the drag coefficients over ocean become 95 to 98

$$Cd_m = \min(Cd_m, Cd_m^{max}) \quad (95)$$

$$Cd_h = \min(Cd_h, Cd_h^{max}) \quad (96)$$

$$z0_m = z0_m^{iter}(2) \quad (97)$$

$$z0_h = z0_h^{iter}(2) \quad (98)$$

A.1.2 land points

For the land points the same equations as for the ocean are used, except for the final calculation of the drag and rugosity coefficients.

Then the neutral coefficients are obtained:

$$\begin{aligned}
R_i &= zg|_{k=1} \frac{z_{td} - z_{tsfcv}}{z_{du}^2 z_{td}} \quad (99) \\
C_d^{neut} &= \frac{C_{KAP}}{\ln(1 + zg|_{k=1}/(gz0_m))} \\
C_{dm}^{neut} &= (C_d^{neut})^2 \\
C_{dh}^{neut} &= C_d^{neut} \left(\frac{C_{KAP}}{\ln(1 + zg|_{k=1}/(gz0_h))} \right)
\end{aligned}$$

the vertical profiles can be computed as in 100 ($R_i < 0$, unstable, selecting by `iflag_corr_insta`) and 102 ($R_i > 0$, stable, selecting via `iflag_corr_sta`)

$$\begin{aligned}
& \left\{ \begin{array}{l} \mu = \ln(\max(z_{0m}/z_{0h}, 0.01)) \\ CM^* = 6.8741 + 2.6933\mu - 0.3601\mu^2 + 0.0154\mu^3 \\ \mathcal{P}_m = 0.5233 - 0.0815\mu + 0.0135\mu^2 - 0.001\mu^3 \\ CH^* = 3.2165 + 4.3431\mu + 0.536\mu^2 - 0.0781\mu^3 \\ \mathcal{P}_h = 0.5802 - 0.1571\mu + 0.0327\mu^2 - 0.0026\mu^3 \\ C_h = \frac{CH^* BC_{KAP}}{\ln(z_{0m} + zg|_{k=1}/(gz_{0m}))} \frac{C_{KAPT}}{\ln(z_{0h} + zg|_{k=1}/(gz_{0h}))} \left(\frac{zg|_{k=1}}{gz_{0h}}\right)^{\mathcal{P}_h} \\ C_m = \frac{CM^* BC_{KAP}}{\ln(z_{0m} + zg|_{k=1}/(gz_{0m}))} \frac{C_{KAP}}{\ln(z_{0m} + zg|_{k=1}/(gz_{0m}))} \left(\frac{zg|_{k=1}}{gz_{0m}}\right)^{\mathcal{P}_m} \\ \mathcal{F}_m = 1 - \frac{BR_i}{1 + C_m \sqrt{ABS(R_i)}} \\ \mathcal{F}_h = 1 - \frac{BR_i}{1 + C_h \sqrt{ABS(R_i)}} \end{array} \right. \quad (100) \\
& \text{Louis 1982 (2)} \quad \left\{ \begin{array}{l} zu_{cf} = \frac{1}{1 + 3C_B C_C C_{dm}^{neut} \sqrt{abs(R_i)(1 + zg|_{k=1}/(gz_{0m}))}} \\ \mathcal{F}_m = \max\left((1 - 2C_B R_i zu_{cf}), R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left((1 - 3C_B R_i zu_{cf}), R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{Laurent Li (3)} \quad \left\{ \begin{array}{l} \mathcal{F}_m = \max\left(\sqrt{1 - 18R_i}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left(\sqrt{1 - 18R_i}, R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{After ATKE (6)} \quad \left\{ \begin{array}{l} s_m = \frac{2}{\pi}(C_{inf} - cn)\arctan(-R_i/r_{i0}) + cn \\ prandtl = -\frac{2}{\pi}(pr_{asym} - pr_{neut})\arctan(R_i/r_{i1}) + pr_{neut} \\ \mathcal{F}_m = \max\left(s_m^{3/2} \sqrt{C_\epsilon} (1 - R_i/prandtl)^{1/2}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left(\mathcal{F}_m/prandtl, R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{default (Louis 1982)} \quad \left\{ \begin{array}{l} zu_{cf} = \frac{1}{1 + 3C_B C_C C_{dm}^{neut} \sqrt{abs(R_i)(1 + zg|_{k=1}/(gz_{0m}))}} \\ \mathcal{F}_m = \max\left(1 - 2C_B R_i zu_{cf}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left(1 - 3C_B R_i zu_{cf}, R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{drag coeff.} \quad \left\{ \begin{array}{l} Cd_m = C_d^{neut} \mathcal{F}_m \\ Cd_h = C_{drag}^{ter} C_d^{neut} \mathcal{F}_h \end{array} \right. \quad (101)
\end{aligned}$$

For the stable cases previously one applies $R_i = \min(20, R_i)$

$$\begin{aligned}
& \text{Louis 1979 \& Mascart 1995 (1)} \quad \left\{ \begin{array}{l} \mathcal{F}_m = \max\left(\frac{1}{(1 + BPRIMER_i)^2}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \quad (102) \\
& \text{Louis 1982 (2)} \quad \left\{ \begin{array}{l} zs_{cf} = \sqrt{1 + C_D abs(R_i)} \\ \mathcal{F}_m = \max\left(\frac{1}{1 + 2C_B R_i / zs_{cf}}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \max\left(\frac{1}{1 + 3C_B R_i / zs_{cf}}, R_{i,Cd}^{min}\right) \end{array} \right. \\
& \text{Laurent Li (3)} \quad \left\{ \begin{array}{l} \mathcal{F}_m = \max\left(\frac{1}{1 + 10R_i(1 + 8R_i)}, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \\
& \text{King 2001 (4)} \quad \left\{ \begin{array}{l} R_i < C_2/2 \left\{ \begin{array}{l} \mathcal{F}_m = \max\left((1 - R_i/C_2)^2, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \\ \left\{ \begin{array}{l} \mathcal{F}_m = \max\left(C_3(C_2/R_i)^2, R_{i,Cd}^{min}\right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \end{array} \right.
\end{aligned}$$

$$\begin{aligned}
& \text{Monin - Obukhov (5)} \quad \left\{ \begin{array}{l} R_i < 1/\alpha \left\{ \begin{array}{l} \mathcal{F}_m = \max \left((1 - \alpha R_i)^2, R_{i,Cd}^{min} \right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \\ \left\{ \begin{array}{l} \mathcal{F}_m = \max \left(1e-7, R_{i,Cd}^{min} \right) \\ \mathcal{F}_h = \mathcal{F}_m \end{array} \right. \end{array} \right. \\
& \text{After ATKE (6)} \quad \left\{ \begin{array}{l} s_m = \max \left(0, cn(1 - R_i/R_{ic}) \right) \\ prandtl = pr_{neut} + R_i pr_{slope} \\ \mathcal{F}_m = \max \left(s_m^{3/2} \sqrt{C_\epsilon} (1 - R_i/prandtl)^{1/2}, R_{i,Cd}^{min} \right) \\ \mathcal{F}_h = \max \left(\mathcal{F}_m/prandtl, R_{i,Cd}^{min} \right) \end{array} \right. \\
& \text{Louis 1982 (default)} \quad \left\{ \begin{array}{l} z_{s_{cf}} = \sqrt{1 + C_D abs(R_i)} \\ \mathcal{F}_m = \max \left(\frac{1}{1+2C_B R_i/z_{s_{cf}}}, R_{i,Cd}^{min} \right) \\ \mathcal{F}_h = \max \left(\frac{1}{1+3C_B R_i/z_{s_{cf}}}, R_{i,Cd}^{min} \right) \end{array} \right. \\
& \text{drag coeff.} \quad \left\{ \begin{array}{l} Cd_m = Cd_m^{neut} \mathcal{F}_m \\ Cd_h = Cd_{drag}^{ter} Cd_h^{neut} \mathcal{F}_h \end{array} \right. \quad (103)
\end{aligned}$$

A.2 screenp_mod

A.2.1 screenp

To get the different $\Delta\chi$ depends on the stability of the boundary layer as it is shown in equations 104, 105

$$\begin{aligned}
& \text{Stable } (\mathcal{L}_0 \geq 0) \quad \left\{ \begin{array}{l} wss > 1.5 \\ \mathcal{L}_0 \leq 1.0 \\ z0_m \leq 1.0 \end{array} \right\} \left\{ \begin{array}{l} \Delta u = \frac{u^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z0_m} + 1 \right) + \min(5, 5(z_{ref} - z0_m)/\mathcal{L}_0) \right] \\ \Delta te = \frac{te^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z0_m} + 1 \right) + \min(5, 5(z_{ref} - z0_m)/\mathcal{L}_0) \right] \\ \Delta qv = \frac{qv^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z0_m} + 1 \right) + \min(5, 5(z_{ref} - z0_m)/\mathcal{L}_0) \right] \end{array} \right. \quad (104) \\
& \left\{ \begin{array}{l} \Delta u = 0.1 wss|_{k=1} \\ \Delta te = 0.1 (ta|_{k=1} - t_{sfc}) \\ \Delta qv = 0.1 (\max(qv|_{k=1}, 0) - \max(qv_{sfc}, 0)) \end{array} \right. \\
& \text{Unstable} \quad \left\{ \begin{array}{l} wss > 5 \\ abs(\mathcal{L}_0) \leq 50 \end{array} \right\} \left\{ \begin{array}{l} x_{tmp} = \left(1 - 16 \frac{z_{ref}}{\mathcal{L}_0} \right)^{1/4} \\ x_{tmp0} = \left(1 - 16 \frac{z0_m}{\mathcal{L}_0} \right)^{1/4} \\ \Delta u \frac{u^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z0_m} + 1 \right) - 2 \ln(0.5(1 + x_{tmp})) + \right. \\ \quad \left. 2 \ln(0.5(1 + x_{tmp0})) - \ln(0.5(1 + x_{tmp}^2)) + \right. \\ \quad \left. \ln(0.5(1 + x_{tmp0}^2)) + 2 \arctan(x_{tmp}) - 2 \arctan(x_{tmp0}) \right] \\ \Delta te \frac{te^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z0_m} + 1 \right) - 2 \ln(0.5(1 + x_{tmp}^2)) + \right. \\ \quad \left. 2 \ln(0.5(1 + x_{tmp0}^2)) \right] \\ \Delta qv \frac{qv^*}{\kappa} \left[\ln \left(\frac{z_{ref}}{z0_m} + 1 \right) - 2 \ln(0.5(1 + x_{tmp}^2)) + \right. \\ \quad \left. 2 \ln(0.5(1 + x_{tmp0}^2)) \right] \end{array} \right. \quad (105) \\
& \left\{ \begin{array}{l} \Delta y = 0.5 wss \\ \Delta te = 0.5 (ta|_{k=1} - t_{sfc}) \\ \Delta qv = 0.5 (\max(qv|_{k=1}, 0) - \max(qv_{sfc}, 0)) \end{array} \right.
\end{aligned}$$

A.3 screenc_mod.F90

A.3.1 screenc

First the drag coefficients Cd_m^{ref} and Cd_h^{ref} are recomputed using the reference values $wss_{ref}, ta_{ref}, qv_{ref}, z_{ref}$ using `cdrag` subroutine (see A.1). With the new coefficients compute the new Δ^{corr} (see eq. 106) `ok_prescr_ust` flag to

force the use of u^*

$$\begin{aligned}
 \Delta^{corr} u & \left\{ \begin{array}{l} ok_prescr_ust \\ \Delta u = \frac{u^*}{\sqrt{Cd_m^{ref}}} \end{array} \right\} \left\{ \begin{array}{l} Cd_m = \frac{(ust^*)^2}{1+ws^2} \\ \Delta u = \frac{u^*}{\sqrt{Cd_m}} \end{array} \right. \\
 \Delta^{corr} te & = \frac{te^* \sqrt{Cd_m^{ref}}}{Cd_h^{ref}} \\
 \Delta^{corr} qv & = \frac{qv^* \sqrt{Cd_m^{ref}}}{Cd_h}
 \end{aligned} \tag{106}$$