Prognostic TKE scheme in IFS

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Prognostic TKE scheme in IFS:

Current computation:

– Eddy Mass-Flux (EDMF):

$$\rho \overline{w'\psi'} = -\rho \mathbf{K}_{\psi} \frac{\partial \psi}{\partial z} + M_u \left(\psi_u - \overline{\psi} \right)$$

– Louis / M-O scheme:

$$\mathbf{K}_{\psi} = c_{\psi} \cdot l \cdot f_{\psi}(Ri, \zeta) \cdot \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial z}\right)^2}$$

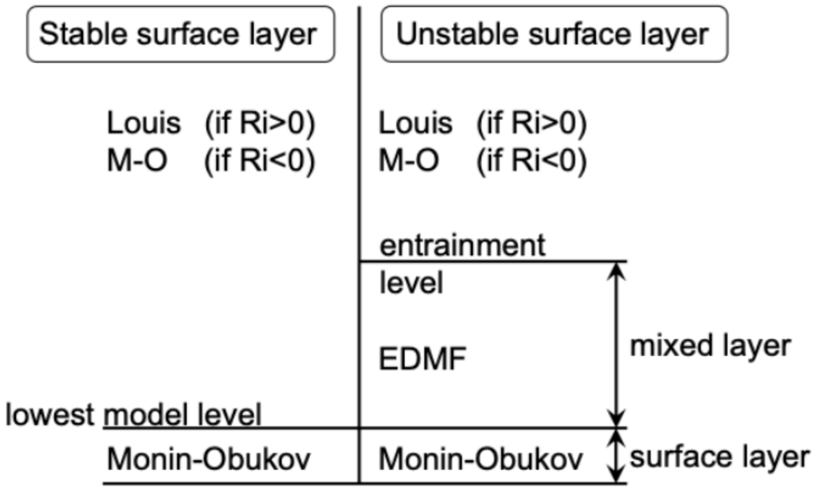

Figure 3.1 *Schematic diagram of the different boundary layer regimes.*

Turbulence Kinetic Energy (TKE=$\mathbf{e_k}$) computation:

$$\mathbf{K}_{\psi} = C_{\psi} \cdot L \cdot F_{\psi}(Ri) \cdot \sqrt{\mathbf{e_k}} \qquad \frac{\partial \mathbf{e_k}}{\partial t} = \mathrm{ADV} + \frac{\partial \left(K_{e_k} \frac{\partial \mathbf{e_k}}{\partial z} \right)}{\partial z} + \mathbf{K_M} S^2 - \mathbf{K_H} N^2 - \frac{C_{\epsilon} \mathbf{e_k}^{\frac{3}{2}}}{L}$$

$K_{M/H}$ – turbulence exchange coefficients for momentum and heat/moisture, L – turbulence length scale, F_{ψ} – stability dependency function, C_{ψ}, Cε – closure constants, N^2 – Brunt–Väisälä frequency, S – wind shear, ADV – advection term, Ri – gradient Richardson number

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Prognostic TKE scheme in IFS:

Turbulent diffusion coefficients in TKE scheme

$$K_M = C_K \chi_3(Ri_f^*)\sqrt{e_k}L, \quad K_H = C_3 C_K \phi_3(Ri_f^*)\sqrt{e_k}L$$

- TKE - measure of turb. intensity
- length scale - scale of the problem
- stability functions - influence of stratification
- closure constants

C_K - closure constant, C_3 - inverse Prandtl number at neutrality, Ri_f^* - stability parameter in the form of flux Richardson number:
$Ri_f \equiv (\frac{g}{\theta_v}\overline{\theta_v' w'})/(\overline{u'w'}\frac{\partial u}{\partial z} + \overline{v'w'}\frac{\partial v}{\partial z})$

Prognostic TKE scheme in IFS:

Prognostic TKE equation

$$\frac{de_k}{dt} = \frac{\partial}{\partial z}\left(K_{e_k}\frac{\partial e_k}{\partial z}\right) + ST + BT - \epsilon_k,$$

$$e_k \equiv \frac{\overline{u'u'} + \overline{v'v'} + \overline{w'w'}}{2} \quad \text{-Turbulence Kinetic Energy (TKE),}$$

$$ST \equiv -\overline{u'w'}\frac{\partial u}{\partial z} - \overline{v'w'}\frac{\partial v}{\partial z} \approx K_M S^2 \quad \text{-Shear term,}$$

$$BT \equiv \frac{g}{\theta_v}\overline{\theta_v' w'} = E_{q_t}\overline{q_t' w'} + E_{\theta_l}\overline{\theta_l' w'} \approx -K_H N^2 \quad \text{-Buoyancy term}$$

$$\epsilon_k \equiv \frac{2\,e_k}{\tau_k} = C_\epsilon \frac{e_k^{\frac{3}{2}}}{L} \quad \text{-Dissipation term}$$

ST - shear term, BT - buoyancy term, K_{e_k} - turb. exchange coefficients for e_k; τ_k and τ_k - dissipation time scale; E_{q_t} and E_{θ_l} - cloud-dependent weights, C_ϵ - closure constant, S - wind shear, N - 'moist' Brunt-Väisälä Frequency Frequency (BVF).

Prognostic TKE scheme in IFS:

- The already implemented TKE scheme has been updated and recalibrated:
    - The turbulence length scale re-formulation
    - The stability dependency functions update
    - Cloud-dependent stability parameter introduction
    - Partial equilibrium computation of the TKE source terms
    - Explicit inclusion of the advection term in the TKE solver
    - Utilization of the Estimated Inversion Strength (EIS) index to identify the stratocumulus regime

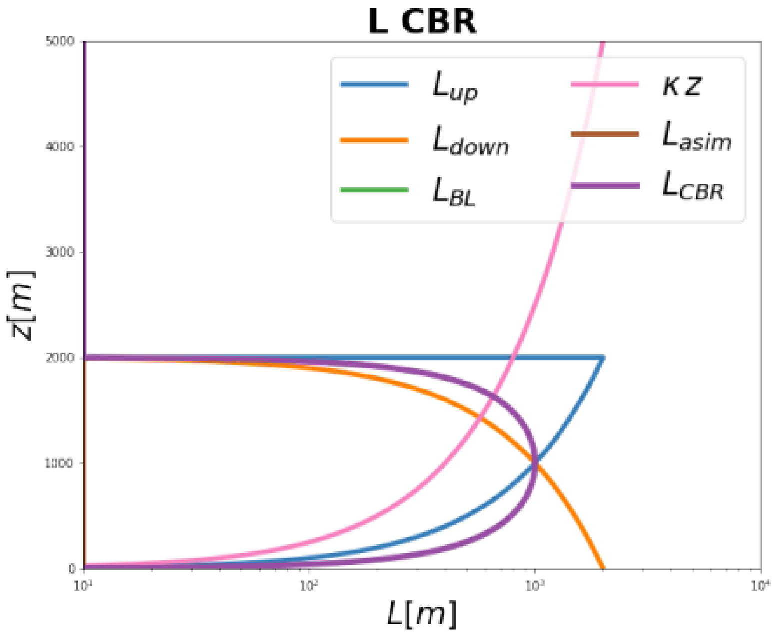
- The modifications have significantly improved the scores compared to the original calibration of the TKE (wind in UTLS, LCC in Stratocumulus, …).
- The TKE scheme compared to the current operational configuration shows a mix of positive (10 ff, geopotential) and negative (tropics) changes in forecast-only experiments.
- There is further improvement in the TKE scheme's performance when run with its own analysis (reduction of spin-up).

The turbulence length scale:

Length scale formulations in CBR

Bougeault and Lacarrere (1989) (L_{BL}):

$$
\begin{aligned}
L_{BL} &= \left(0.5\, L_{up}^{-\frac{2}{3}} + 0.5\, L_{down}^{-\frac{2}{3}}\right)^{-\frac{3}{2}}, \\
&\int_{z}^{z+L_{up}} \frac{g}{\theta_{vr}}(\theta_v(z) - \theta_v(z'))\, dz' = e_k(z), \\
&\int_{z-L_{down}}^{z} \frac{g}{\theta_{vr}}(\theta_v(z') - \theta_v(z))\, dz' = e_k(z), \\
L_{CBR} &= \max\left(\min\left(\kappa z, L_{asim}\right), L_{BL}\right)
\end{aligned}
$$



$\kappa = 0.4$ is the von Kármán constant, $L_{asim} = 10.0m$ - asimptotic length scale

The turbulence length scale:

Wind shear contribution to L according to de Rodier et al. (2017)

- prevents over-estimation of L in stable stratification with strong shear
-

$$L = \frac{(C_K\, C_\epsilon)^{\frac{1}{4}}}{C_K} \left(\frac{L_{up}^{-\frac{2}{3}} + L_{down}^{-\frac{2}{3}}}{2} \right)^{-\frac{3}{2}},$$

$$\int_z^{z+L_{up}} \frac{g}{\theta_{vr}} \left(\theta_v(z) - \theta_v(z') + \mathbf{C_0} \cdot \sqrt{\mathbf{e_k}} \cdot \mathbf{S(z')}\right)\, dz' = e_k(z),$$

$$\int_{z-L_{down}}^{z} \frac{g}{\theta_{vr}} \left(\theta_v(z) - \theta_v(z') + \mathbf{C_0} \cdot \sqrt{\mathbf{e_k}} \cdot \mathbf{S(z')}\right)\, dz' = e_k(z),$$

The turbulence length scale:

New calibration of the length scale formulations

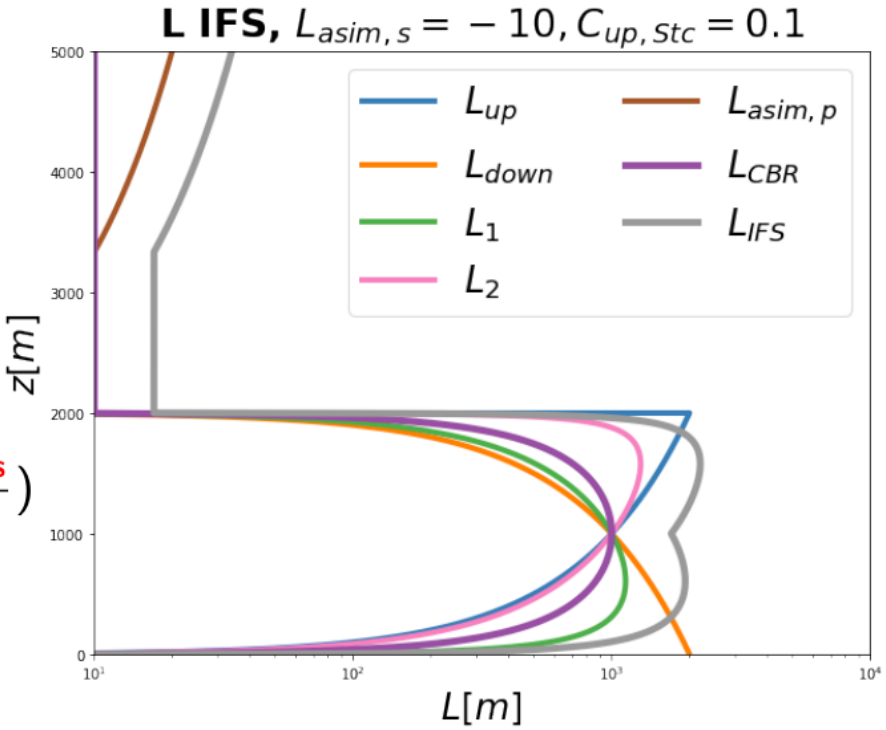
$$L_1 = \left(C_{up} L_{up}^{-\frac{2}{3}} + (1 - C_{up}) L_{down}^{-\frac{2}{3}} \right)^{-\frac{3}{2}},$$

$$L_2 = \left(C_{up,Stc} L_{up}^{-\frac{2}{3}} + (1 - C_{up,Stc}) L_{down}^{-\frac{2}{3}} \right)^{-\frac{3}{2}},$$

$$L_{1,2} = \max(L_1, L_2)$$

$$L_{asim,p} = L_{asim} - \max(0.0, (z_{Lm} - z) \frac{L_{asim} - L_{asim,s}}{z_{Lm}})$$

$$L_{IFS} = C_{LSC} \max(\min(\kappa z, L_{asim}), L_{1,2}, L_{asim,p}),$$

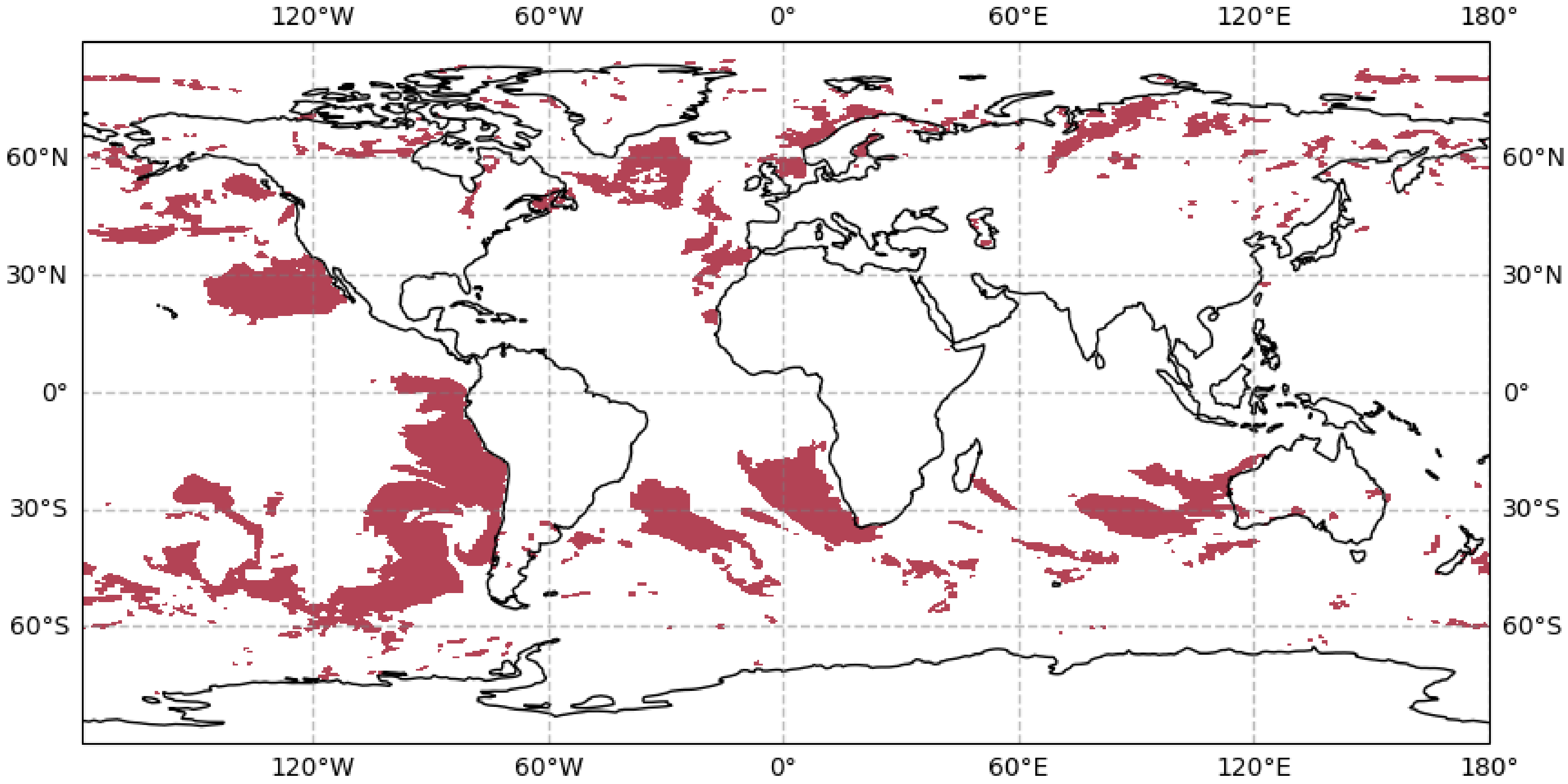


$L_{asim,s}$, $C_{up,Stc}$ - functions of EIS

$C_{LSC} = 1.7$, $z_{Lm} = 1e4m$, $C_{up} = 0.8$, $L_{asim} = 50.0m$ - calibration constants.

The turbulence length scale:

- Identification of stratocumulus regime via EIS>4, Bowen ratio<0.25, and negative sensible heat flux (snapshot):



The turbulence length scale:

The EIS dependence:

$$EIS < EIS^{StCuL} \quad : \quad L_{asim,s} = 30.0, \ \ C_{up,Stc} \equiv C_{up} = 0.8$$

$$EIS^{StCuL} < EIS < EIS^{StCuH} \quad : \quad \mathbf{L_{asim,s} = -10.0, \ \ C_{up,Stc} = 0.2}$$

$$EIS > EIS^{StCuH} \quad : \quad L_{asim,s} = 10.0, \ \ C_{up,Stc} \equiv C_{up} = 0.8$$

- linear intepolation of values between regimes on ΔEIS interval

$EIS^{StCuL} = 2.0$, $EIS^{StCuH} = 14.0$, $\Delta EIS = 1.0$ - calibration constants.

The stability dependence functions:

In CBR:

- $$\phi_3 = \frac{1}{1 + C_\theta\, C_{\epsilon_\theta} \frac{g}{\theta_{vl}} \frac{L^2}{e_k} \frac{\partial \theta_{vl}}{\partial z}},$$

- stability dependency in ϕ_3 determined by the **local vertical gradient of θ_{vl}** and **non-local estimate of wind shear** obtained from TKE and L

- N_2 in **buoyancy source term** computed internally in a different way

- **no anisotropy for momentum**: $\chi_3 = 1.0$

θ_{vl} - virtual potential temperature, C_θ, C_{ϵ_θ} - closure constants

The stability dependence functions:

$$\chi_3(Ri) = \frac{1 - \frac{Ri_f}{R}}{1 - Ri_f} \quad , \quad \phi_3(Ri) = \frac{1 - \frac{Ri_f}{P}}{1 - Ri_f} \quad ,$$

$$1 \geq R > 0 \quad , \quad R \geq P > 0 \quad ,$$

- more flexible

P and R - determine the shape of the stability functions according to Bastak Duran et al. (2014)

The stability dependence functions:

Cloud cover dependence:

- according to Marquet and Geleyn (2013):

$$Ri_f = \frac{K_H(Ri_f)}{K_M(Ri_f)} Ri = \frac{C_3 R(P - Ri_f)}{R(P - Ri_f)} Ri,$$

$$Ri = \frac{N_1^2(\mathbf{C})}{S^2}$$

$$N_1^2(\mathbf{C}) = g\, M(\mathbf{C}) \frac{c_{pd}}{c_p} \frac{\partial \ln(\theta_{\mathbf{s}})}{\partial z} + g \frac{\partial \ln(\theta_{\mathbf{s}})}{\partial z} + g\, M(\mathbf{C}) \left[F(\mathbf{C})(1 + r_v) \frac{R_v}{R} - \Lambda \right] \frac{\partial(q_t)}{\partial z}$$

$M(C)$ and $F(C)$ - functions of C, $\Lambda = 5.87$ - closure constant, $R = R_d\, q_d + R_v\, q_v$, $c_p = c_{pd}\, q_d + c_{pv}\, q_v + c_l\, q_l$, $r_v = q_v / q_d$, q_d - specific content for dry air

The stability dependence functions:

Update:

- sharper transition via local gradients
- explicit dependence on prognostic cloud fraction, C
- consistency with source terms, because N_1^2 used also in **buoyancy source term** computation: $BT = -K_H N_1^2$

Partial equilibrium computation of the TKE source terms:

Stable stratification with strong wind shear

- Under-estimation of turbulent mixing due to low value of TKE.
- Problem with **temporal discretization**: $e_k^{t-}=0 \wedge ST^{t0} + BT^{t0} \leq 0 \Rightarrow e_k^{t0}=0$
- TKE source terms are computed using TKE from previous time step:

$$\begin{aligned} ST^{t0} &= K_M^{t0}\left(S^2\right)^{t-} = C_K\, L^{t0}\, \chi_3^{t0} \sqrt{e_k^{t-}} \left(S^2\right)^{t-}, \\ BT^{t0} &= -K_H^{t0}\left(N^2\right)^{t-} = C_3\, C_K\, L^{t0}\, \phi_3^{t0} \sqrt{e_k^{t-}} \left(N^2\right)^{t-}, \end{aligned}$$

^{t0} marks the current time step and index $^{t-}$ marks the previous time step

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Partial equilibrium computation of the TKE source terms:

Stable stratification with strong wind shear

- Solution: the TKE source terms are partly computed from TKE equilibrium conditions:

  $$ST = (R_{eq}\, K_M^{eq} + (1 - R_{eq})\, K_M)\, S^2,$$

  $$BT = (R_{eq}\, K_H^{eq} + (1 - R_{eq})\, K_H)\ N^2,$$

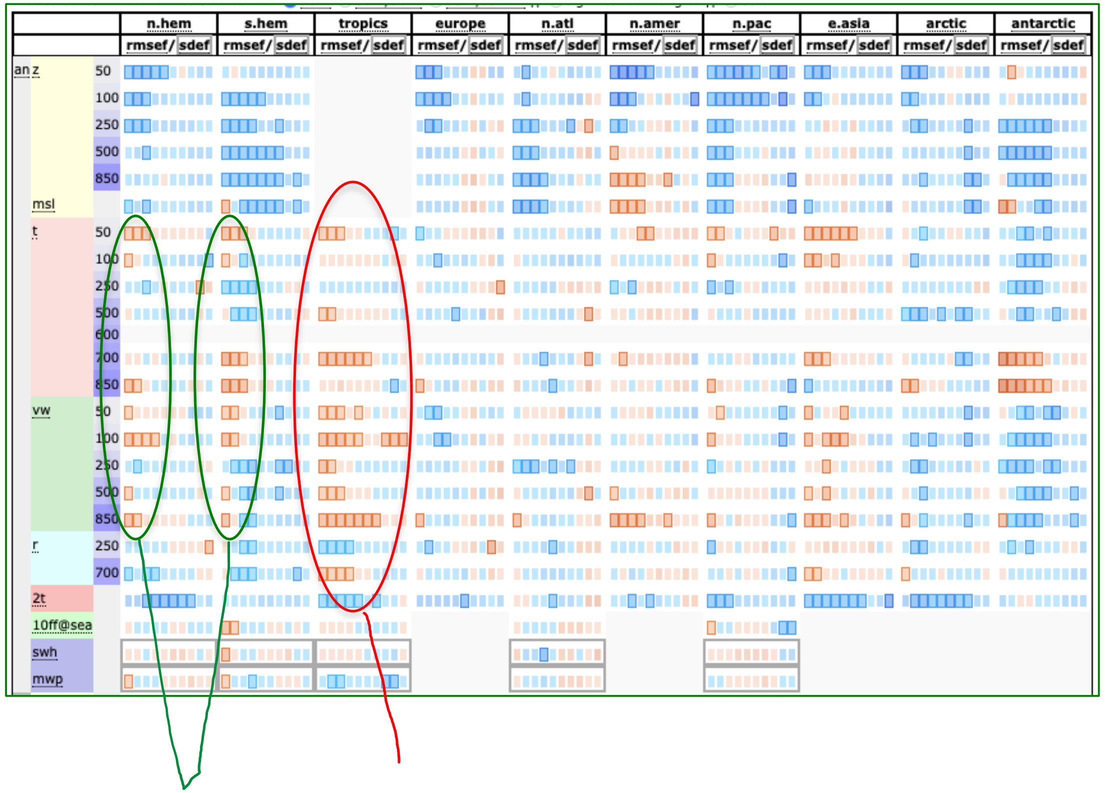
- $K_M^{eq} and K_H^{eq}$ can be taken from current first order scheme, or they can be computed consistently from equilibrium TKE, $\tilde{e_k}$:
  - can be taken from **current first order scheme**
  - or they can be computed consistently from **equilibrium TKE**:

    $$\tilde{\mathbf{e}}_{\mathbf{k}} = \frac{C_K}{C_\epsilon} L^2\, (\chi_3 - C_3 \phi_3 Ri)\, S^2$$

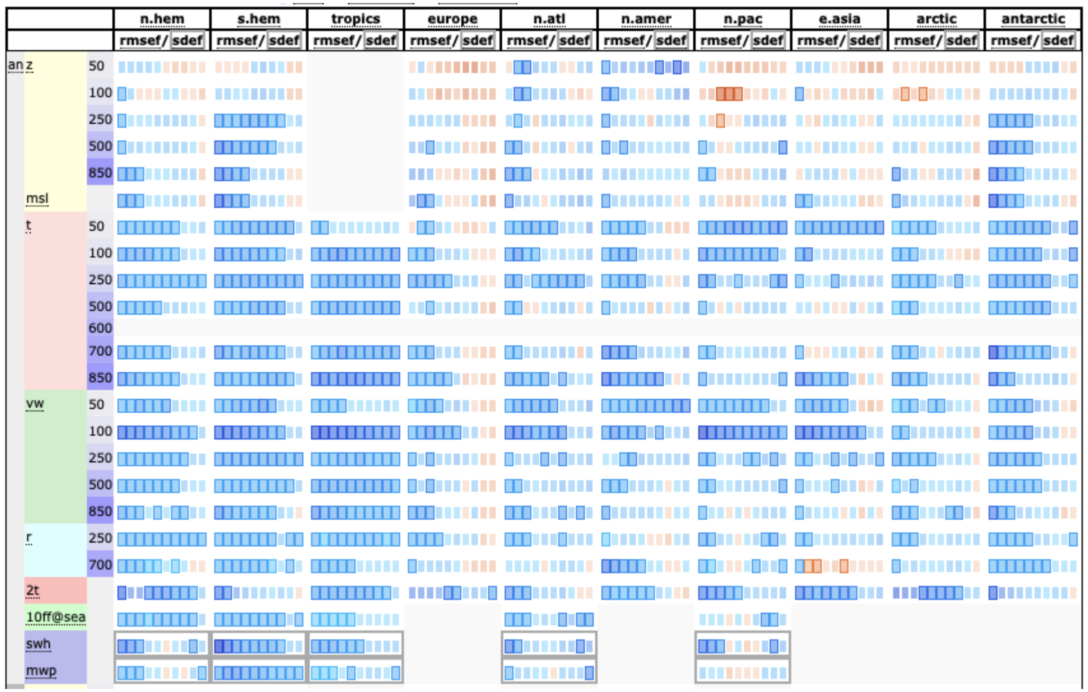
$R_{eq} = 0.5$ is a calibration constant

- Combined summer and winter one-month period forecast RMSE evaluated against the operational analysis (TCO399):

TKE scheme vs. operational



TKE scheme vs. original TKE setup

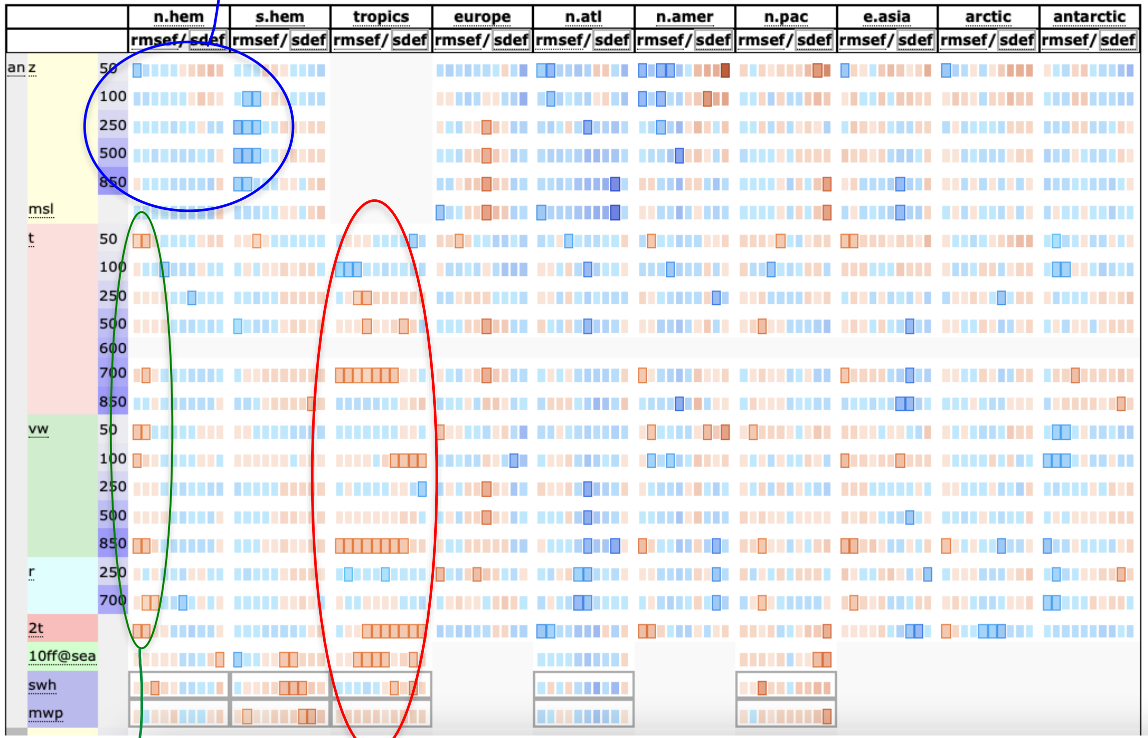


- Combined summer and winter two-week period RMSE:

TKE scheme with its own analysis vs. operational (TCO399)

geopotential improvement

evaluated against their own analysis:



evaluated against observation:

Inconsistency with TL/AD?

Tropics: T 700 hPa + VW 850 hPa + T 2m + 10ff

10ff and TCC improvement

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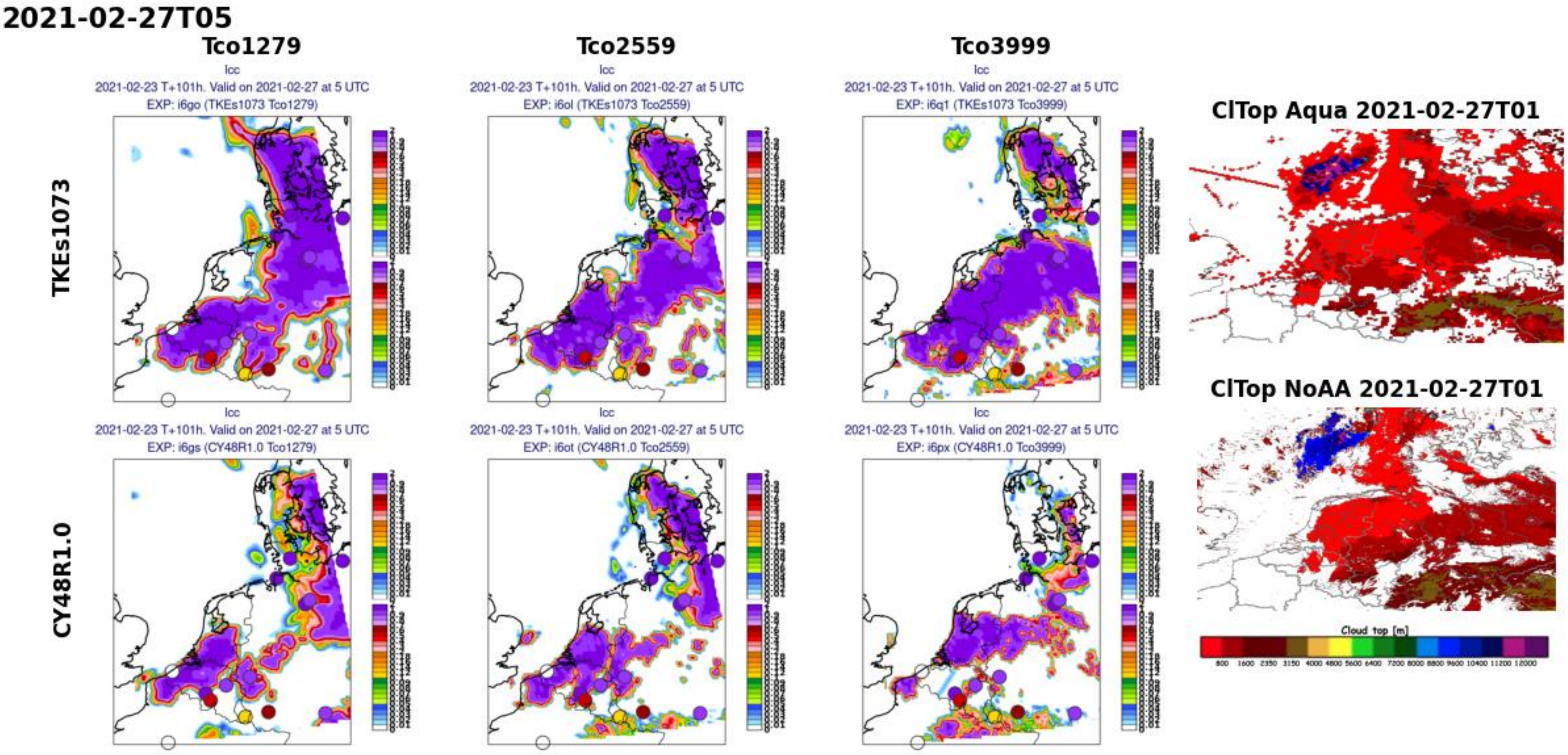
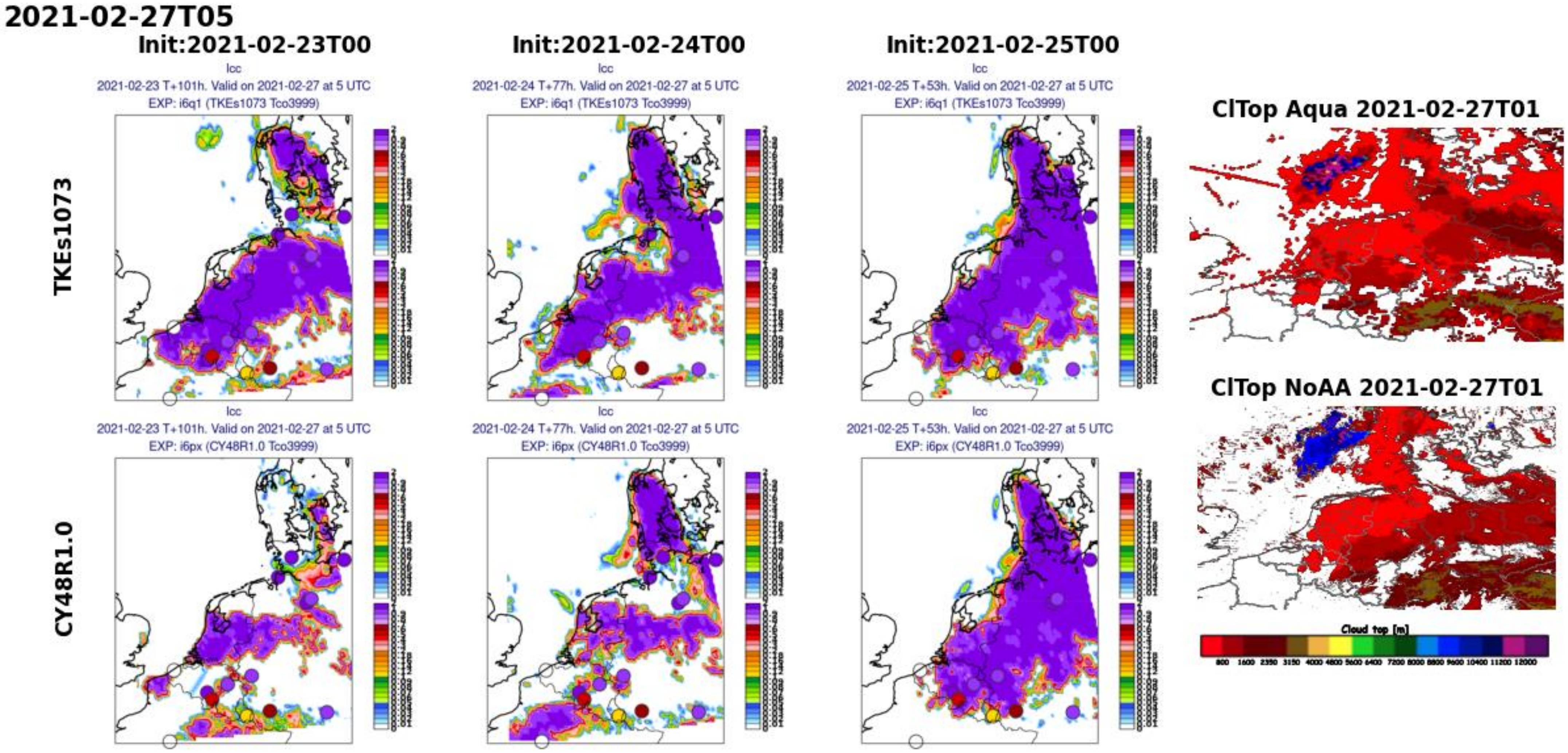
TKE scheme vs. control, LCC, different resolutions



TKE scheme vs. control, LCC, different lead times



- Future plans:
    - Fix remaining issues in the tropics
    - Investigate interactions of the TKE scheme with other parameterizations
    - Test the TKE scheme at higher resolutions

Thank you for your attention!