Planetary Boundary Layer 3

Outer layer and model sensitivity

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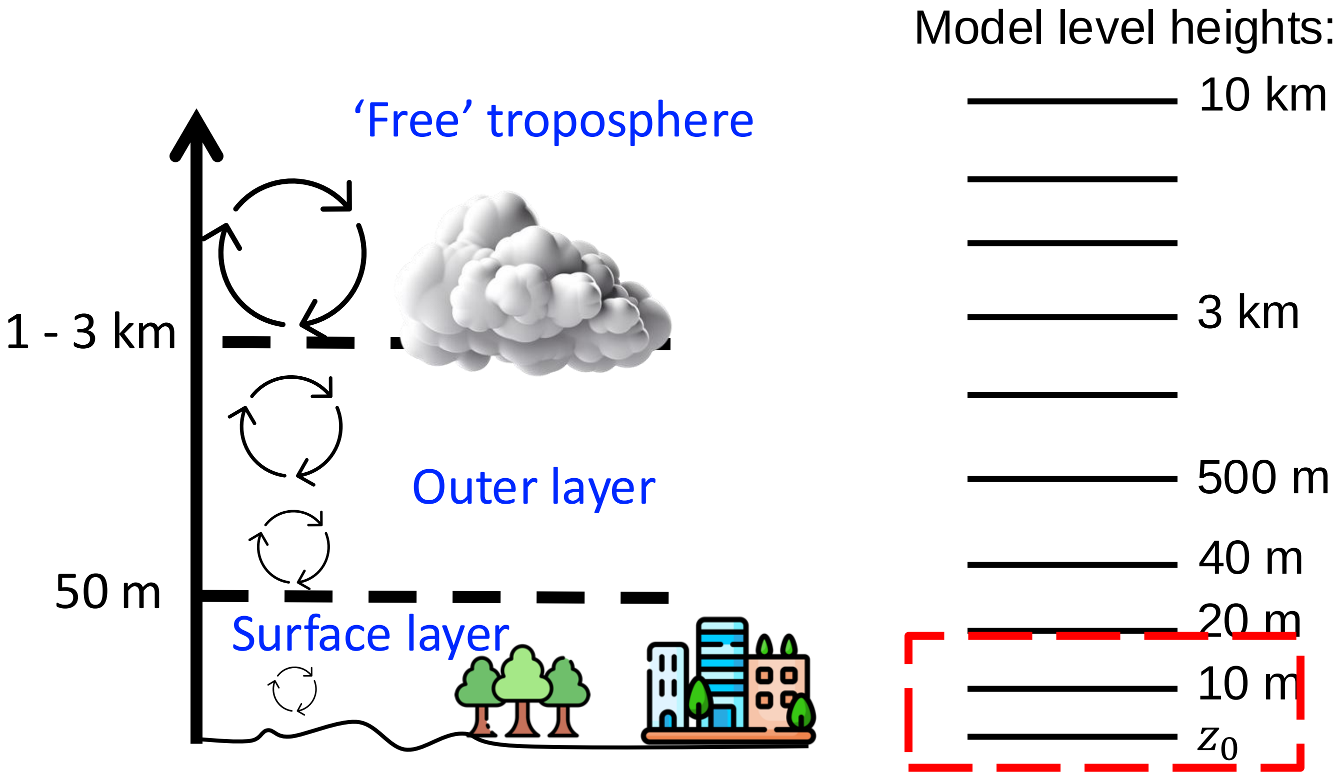
Contents

- K-closure in the outer layer
- Eddy-diffusivity Mass-Flux (non-local transport)
- Description of IFS scheme
- Sensitivity of forecasts to changes in diffusion scheme:
  - Model issues in stable boundary layers
  - Using prognostic TKE

What do we need from a turbulence parametrization scheme?

- Provide turbulent fluxes of heat, momentum, moisture (and tracers) between the surface and the upper atmosphere
- Account for differences in stability and surface properties
- Provide profiles of winds and temperatures at the surface, where the model does not resolve in the vertical
- Provide turbulent mixing throughout the entire atmosphere – the mixed layer, the cloud layer and the stratosphere



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‘Local’ turbulence closure: eddy diffusion above the surface

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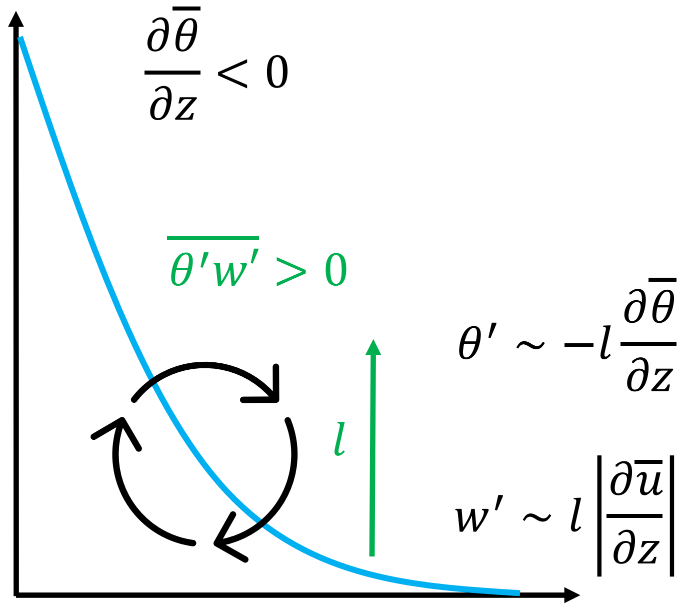
Any quantity ϕ:

$$\overline{\phi' w'} = -K_\phi \frac{\partial \overline{\phi}}{\partial z} = -l^2 \left|\frac{\partial \overline{u}}{\partial z}\right| \frac{\partial \overline{\phi}}{\partial z}$$



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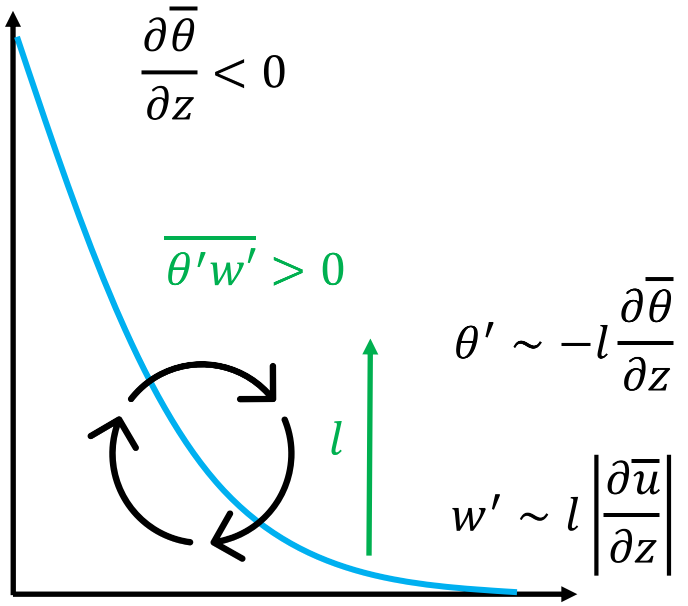
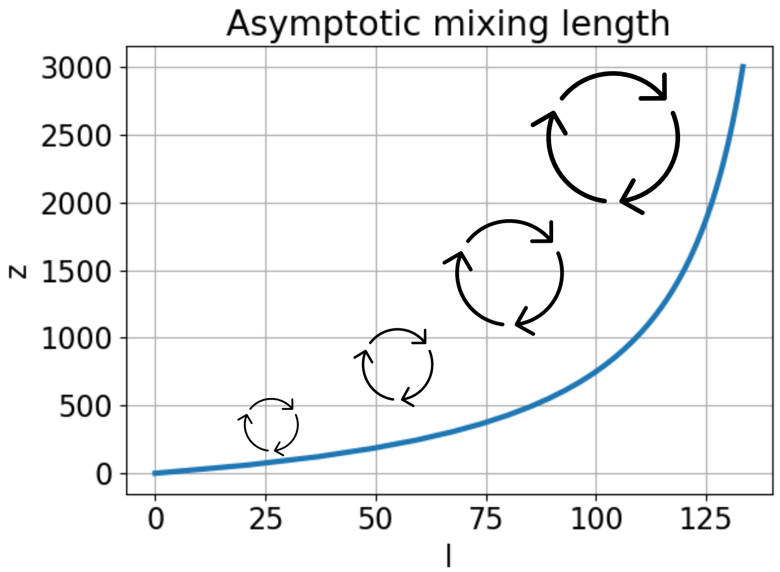


Size of eddies get larger further away from the surface:

$$l \sim \frac{\kappa z \lambda}{\kappa z + \lambda}$$

κ =von-Karman constant

λ =asymptotic mixing length (150 m)



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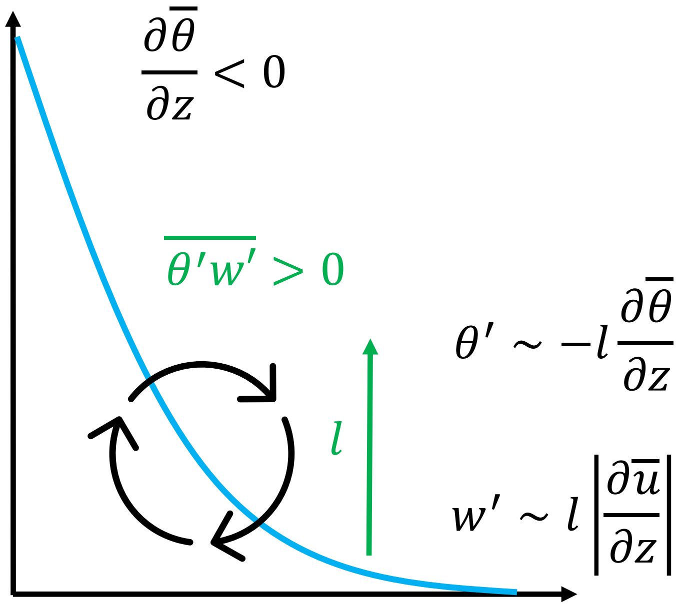
Any quantity ϕ:

$$\overline{\phi' w'} = -K_\phi \frac{\partial \overline{\phi}}{\partial z} = -l^2 \left|\frac{\partial \overline{u}}{\partial z}\right| f_\phi(Ri) \frac{\partial \overline{\phi}}{\partial z}$$



Size of eddies get larger further away from the surface:

$$l \sim \frac{\kappa z \lambda}{\kappa z + \lambda}$$

κ = von-Karman constant
λ = asymptotic mixing length (150 m)

Add stability dependence:

$f_M(Ri), f_H(Ri)$ determined empirically and depend on Ri(z)

No longer using $\frac{z}{L}$, since we are away from the surface

Local similarity theory in the outer layer – making use of the surface stability functions

Any quantity ϕ:

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$$K_\phi = \frac{l^2}{\Phi_\phi(\zeta)\Phi_M(\zeta)} \left| \frac{\partial \overline{u}}{\partial z} \right| = l^2 \left| \frac{\partial \overline{u}}{\partial z} \right| f_\phi(Ri)$$

Use the relation

$$Ri = \zeta \frac{\Phi_H(\zeta)}{\Phi_M^2(\zeta)}$$

to convert $\zeta = \frac{z}{L}$ to the gradient Richardson number in the outer layer

‘Non-Local’ turbulence: eddy-diffusivity mass-flux (EDMF)

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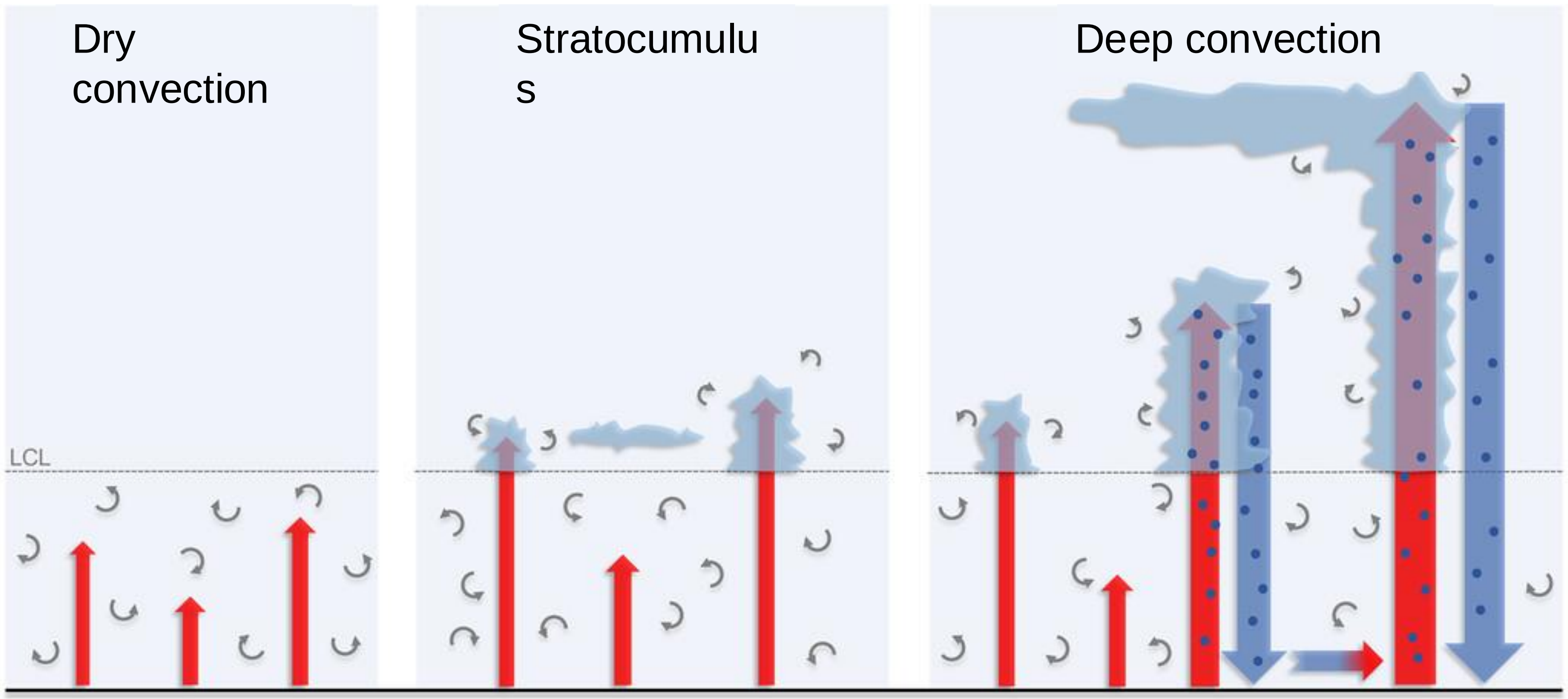
‘Non-Local’ turbulence: eddy-diffusivity mass-flux (EDMF)

Local turbulent diffusion fails in convective boundary layers because it yields unrealistic zero flux in an environment with small gradients



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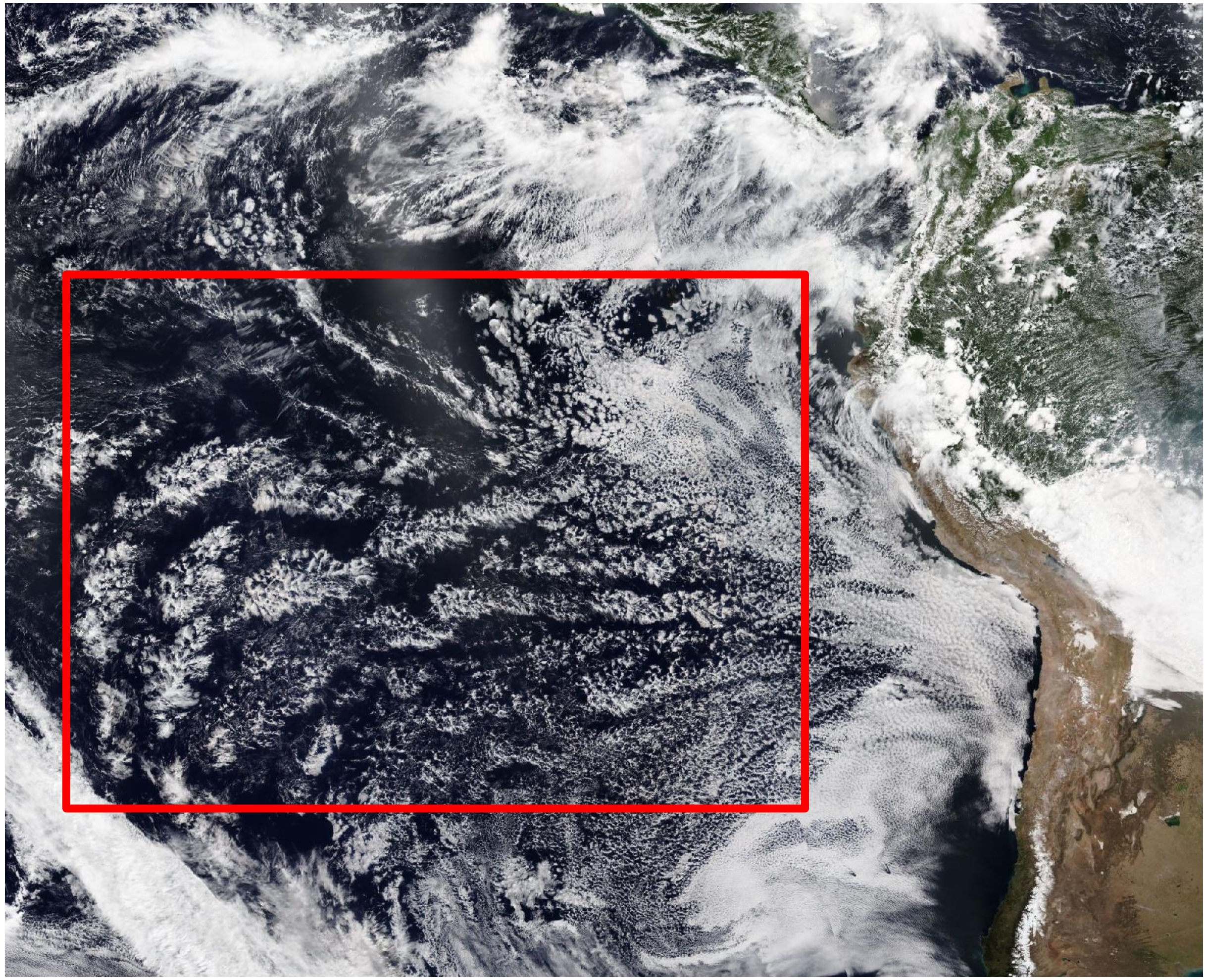
‘Non-Local’ turbulence: eddy-diffusivity mass-flux (EDMF)

In convective boundary layers, the area of strongest updraft is typically much smaller than the environment



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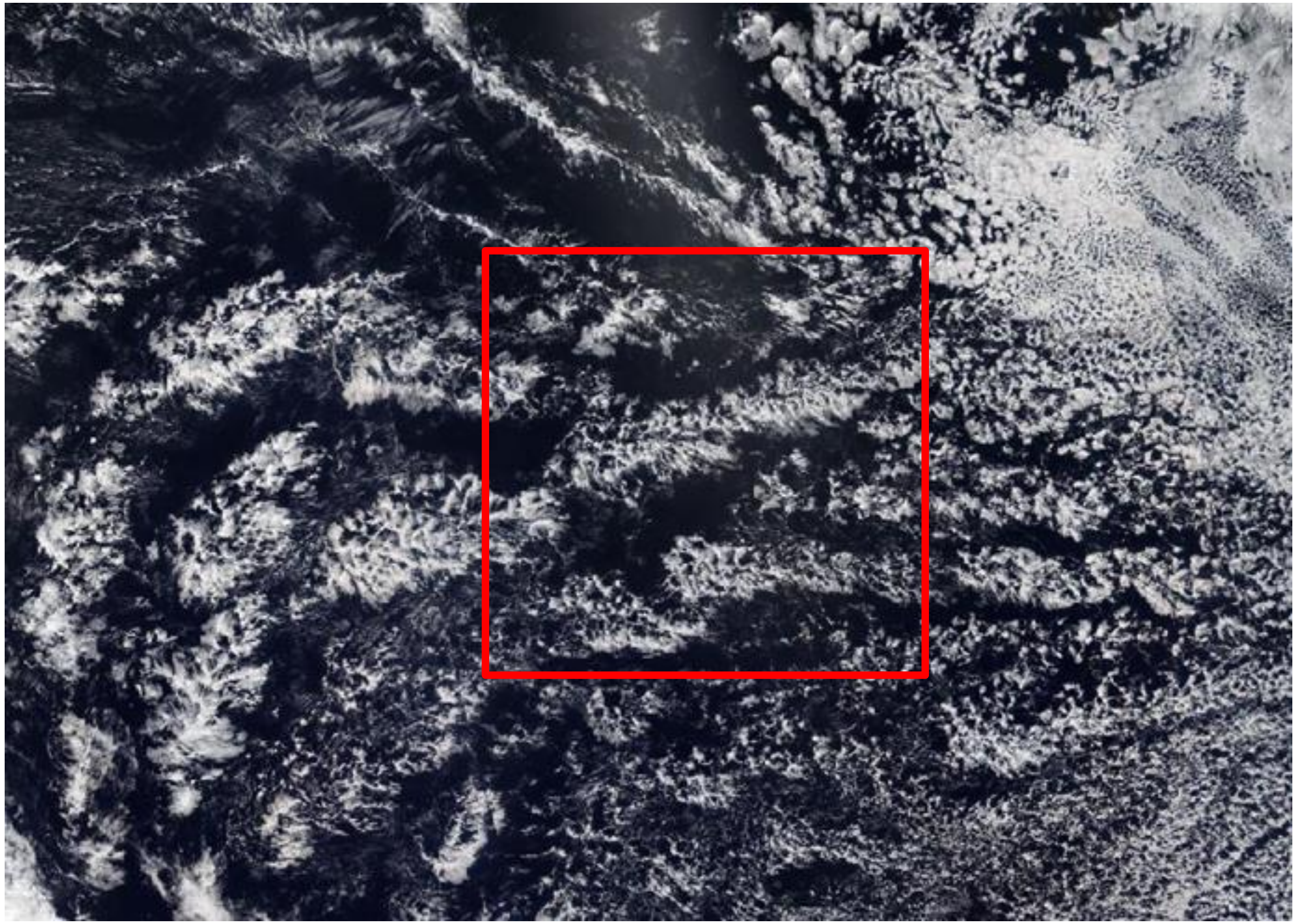

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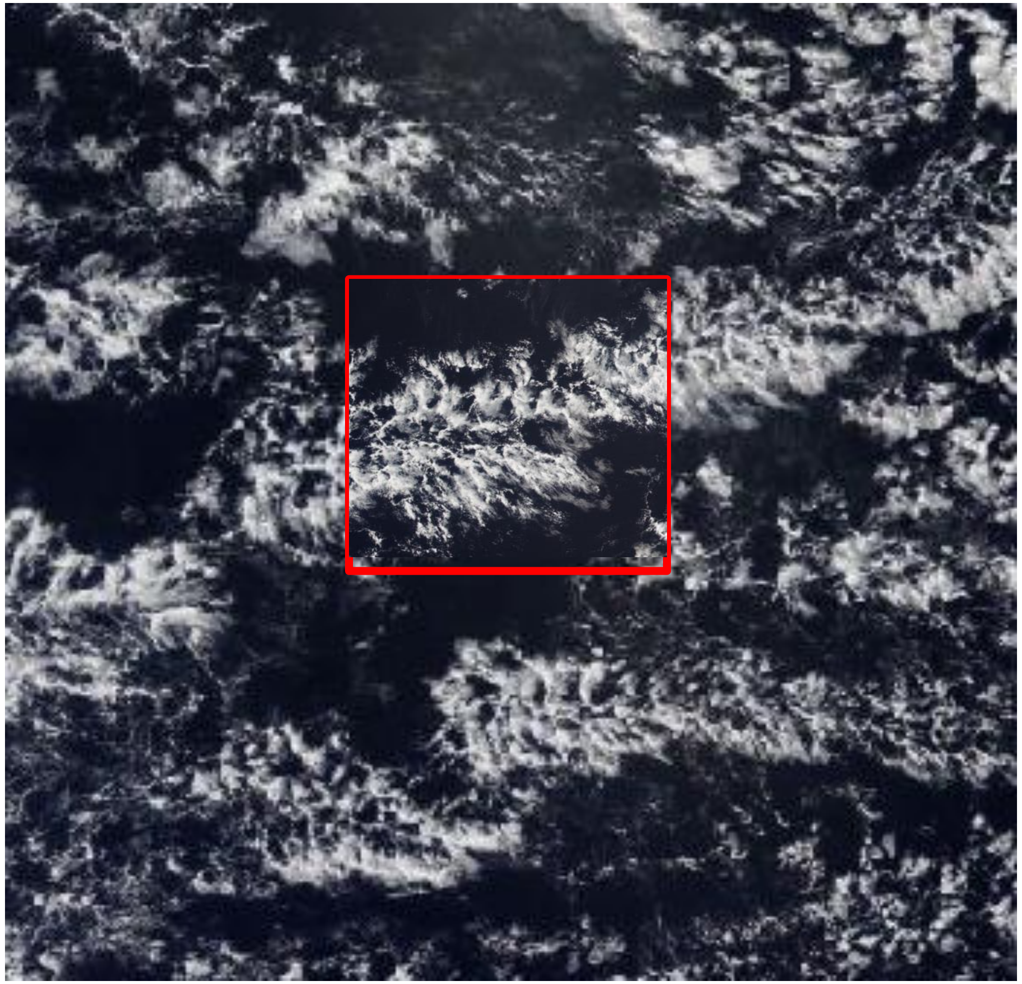

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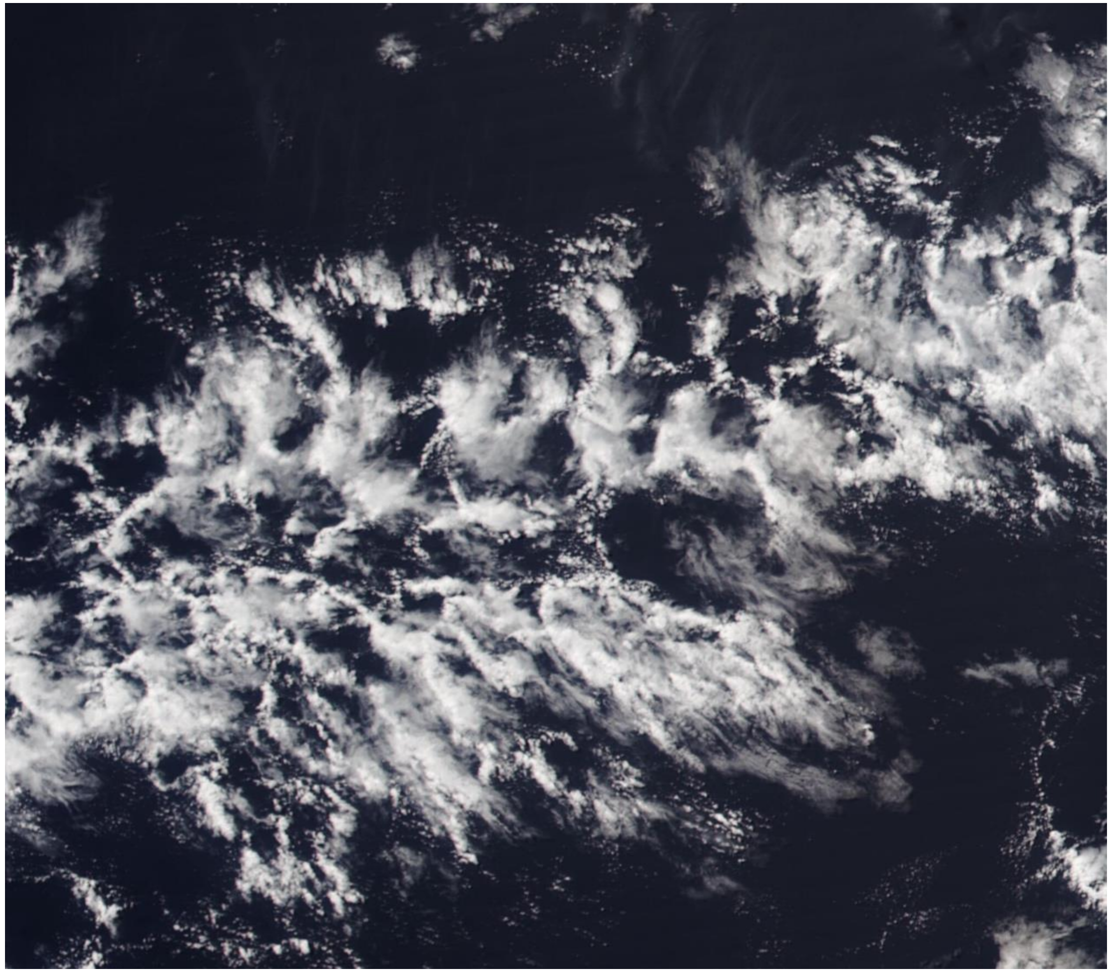
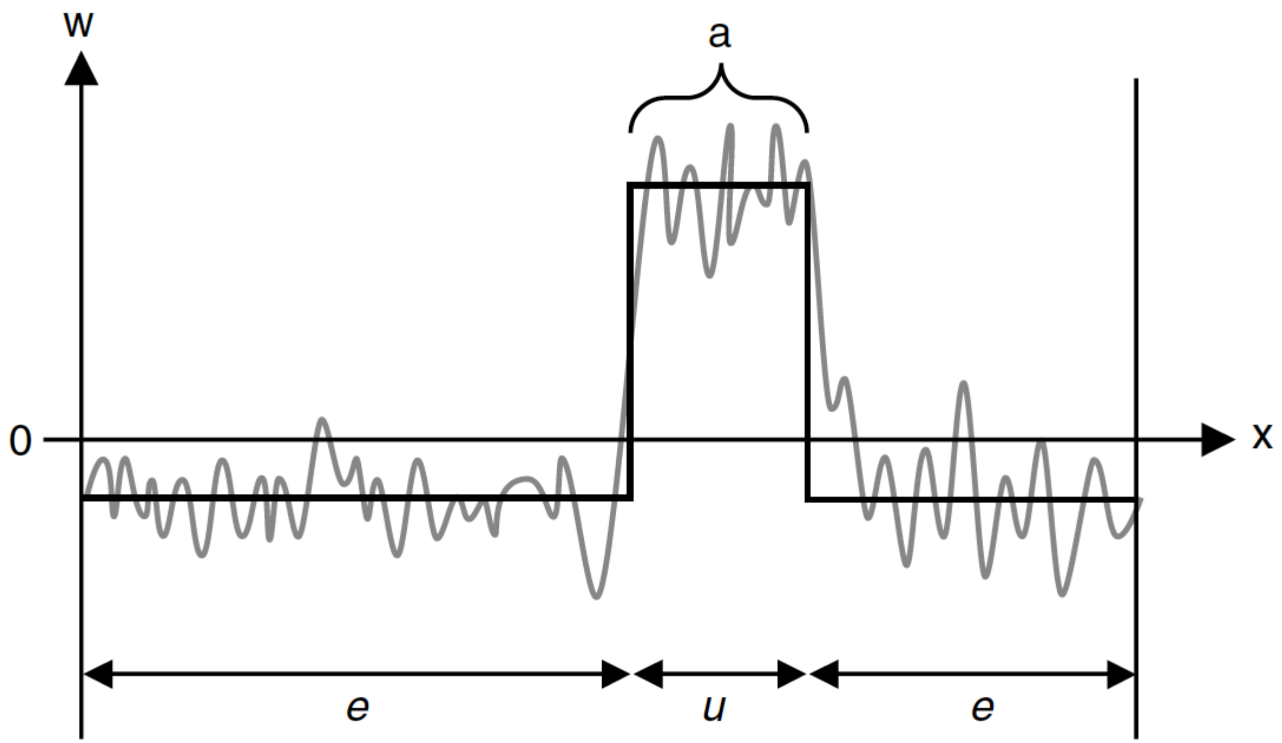


‘Non-Local’ turbulence: eddy-diffusivity mass-flux (EDMF)

Total turbulent flux of ϕ :

$$\overline{\phi' w'} = a\overline{\phi_u' w'} + (1-a)\overline{\phi_e' w'} + a(\overline{w}^u - \overline{w})(\overline{\phi}^u - \overline{\phi}^e)$$



Turbulent flux within the strong updraft region

‘Non-Local’ turbulence: eddy-diffusivity mass-flux (EDMF)

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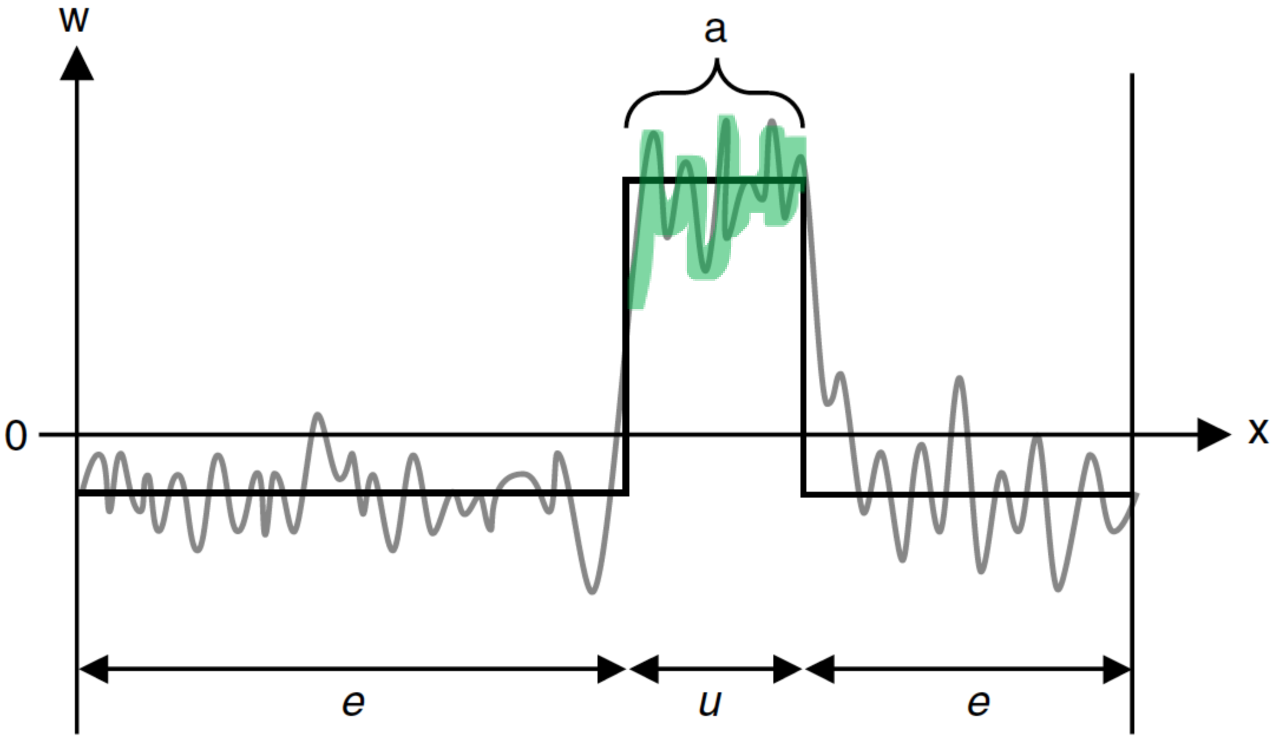
$$\overline{\phi' w'} = a\overline{\phi'_u w'} + (1-a)\overline{\phi'_e w'} + a(\overline{w}^u - \overline{w})(\overline{\phi}^u - \overline{\phi}^e)$$

Subcore
flux



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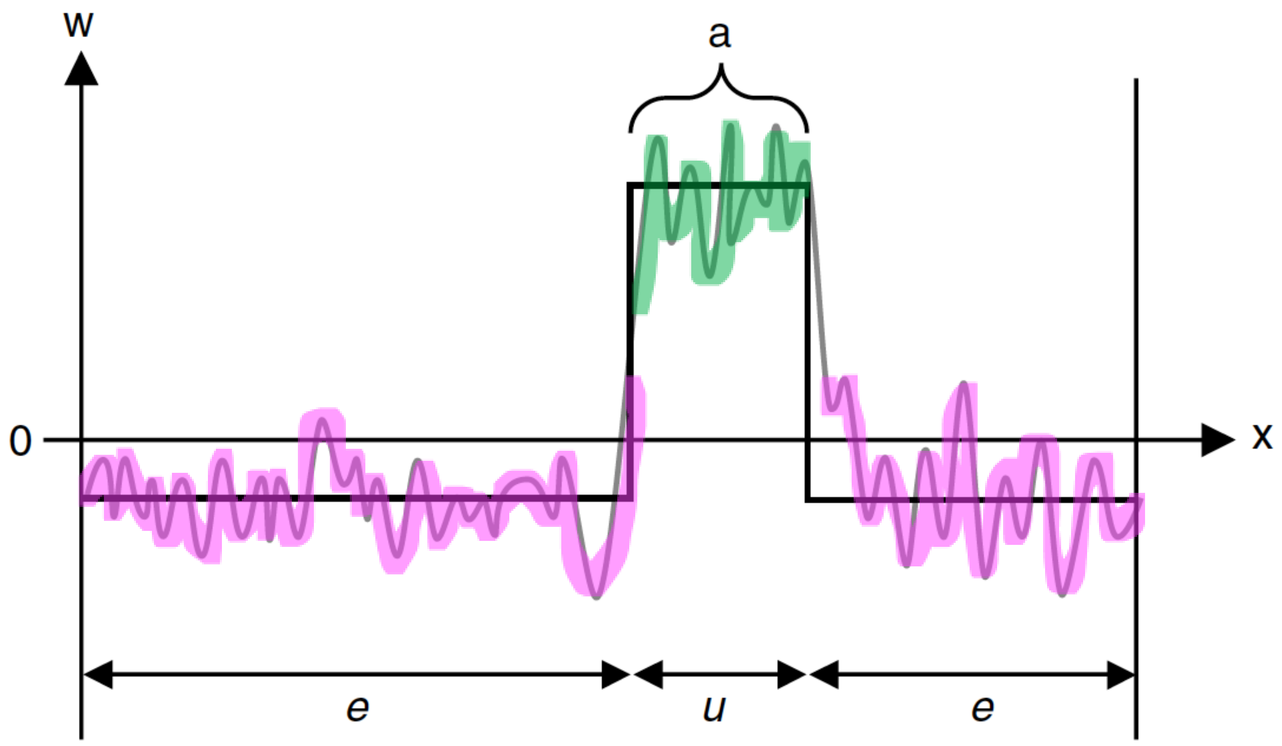
Subcore flux

Environmental flux



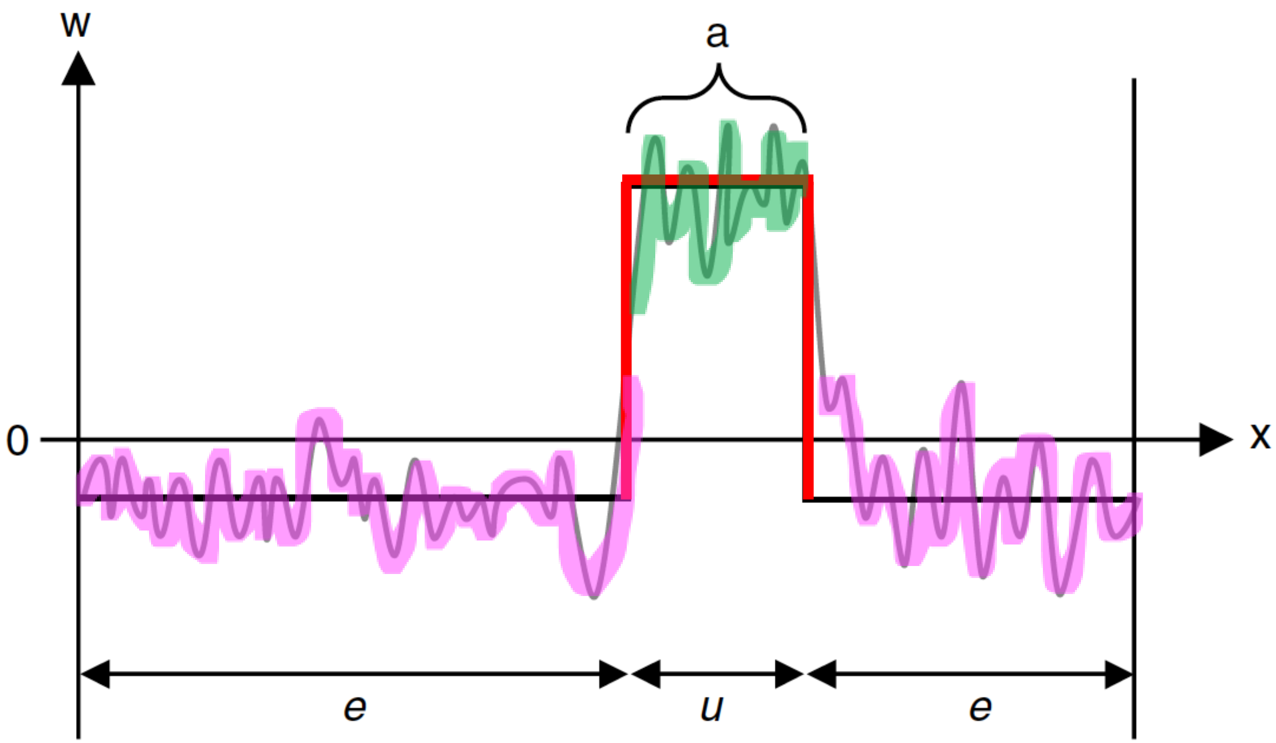
Turbulent flux in the environment outside the strongest updraft

‘Non-Local’ turbulence: eddy-diffusivity mass-flux (EDMF)

Total turbulent flux of ϕ :

$$\overline{\phi' w'} = a\overline{\phi_u' w'} + (1-a)\overline{\phi_e' w'} + a(\overline{w}^u - \overline{w})(\overline{\phi}^u - \overline{\phi}^e)$$

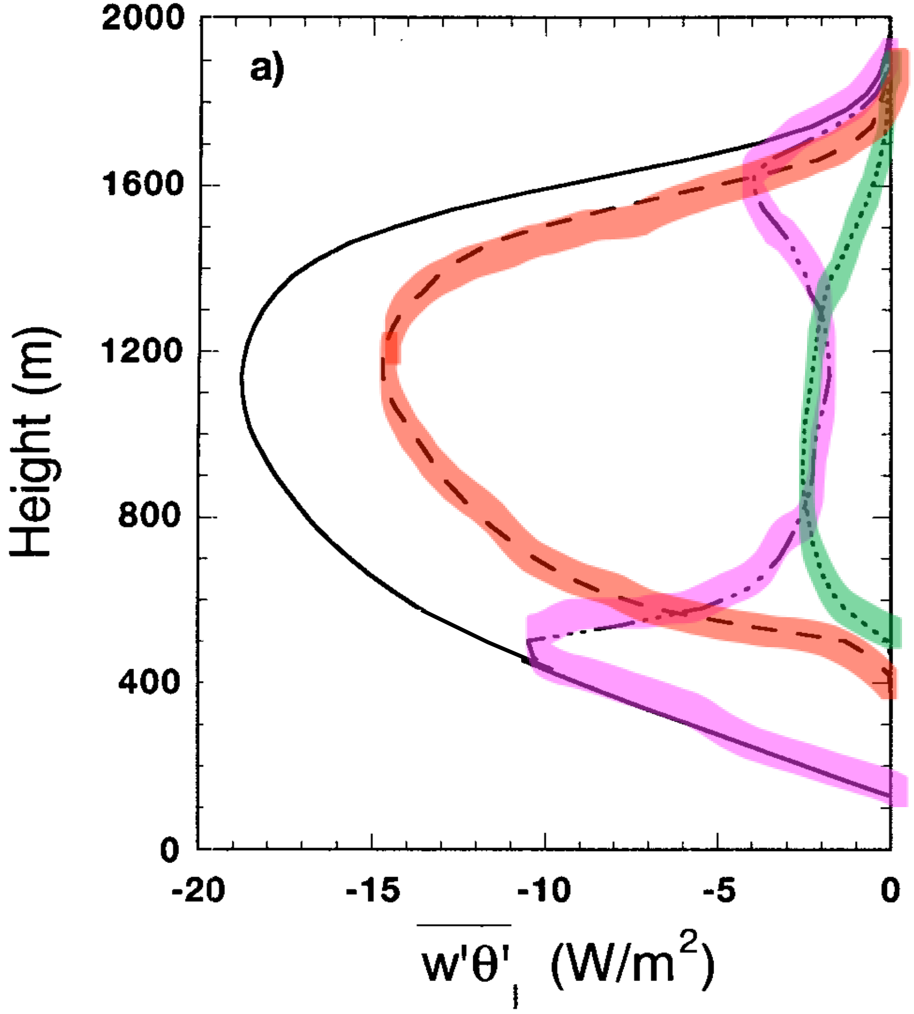
Subcore flux | Environmental flux | Mass flux



Mean flux inside the strongest updraft region

'Non-Local' turbulence: eddy-diffusivity mass-flux (EDMF)

Heat flux from LES



Total turbulent flux of ϕ :

$$\overline{\phi' w'} = a\overline{\phi'_u w'} +$$

Subcore flux

$$(1-a)\overline{\phi'_e w'} +$$

Environmental flux

$$a(\overline{w}^u - \overline{w})(\overline{\phi}^u - \overline{\phi}^e)$$

Mass flux

M-flux covers 80% of the flux for heat and moisture

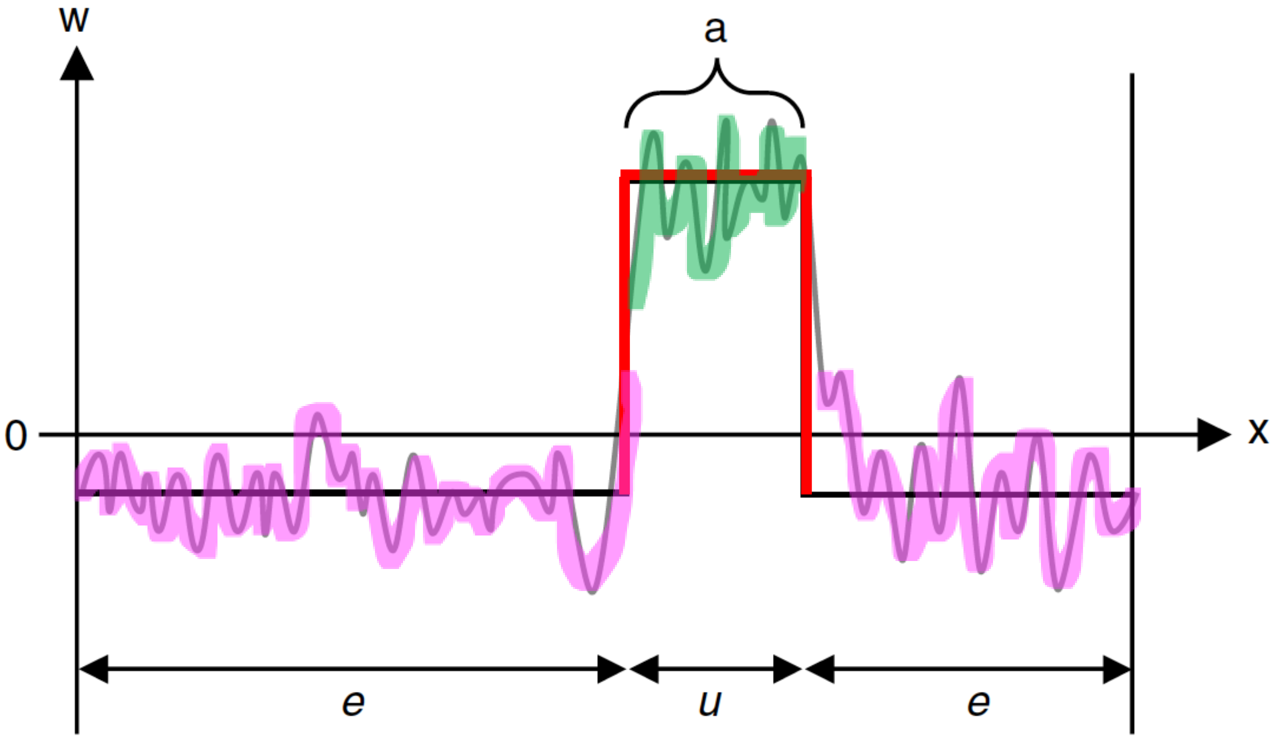
Siebesma & Cuijpers, 1995

'Non-Local' turbulence: eddy-diffusivity mass-flux (EDMF)

Total turbulent flux of ϕ :

$$\overline{\phi' w'} = a\overline{\phi_u' w'} + (1-a)\overline{\phi_e' w'} + a(\overline{w}^u - \overline{w})(\overline{\phi}^u - \overline{\phi}^e)$$

Subcore flux | Environmental flux | Mass flux



Assumptions made:

1. Area of strongest updraft is small compared with the environment (a<<1). Subcore flux is neglected

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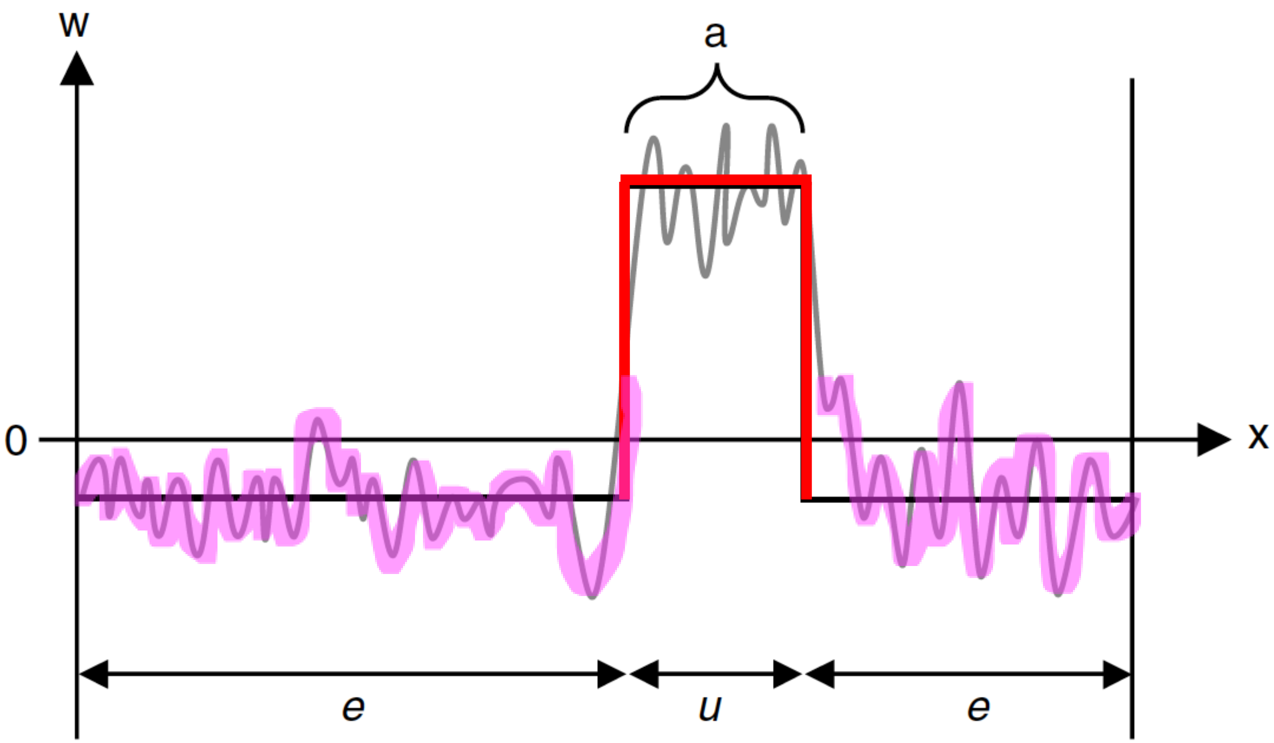
Environmental flux

Mass flux



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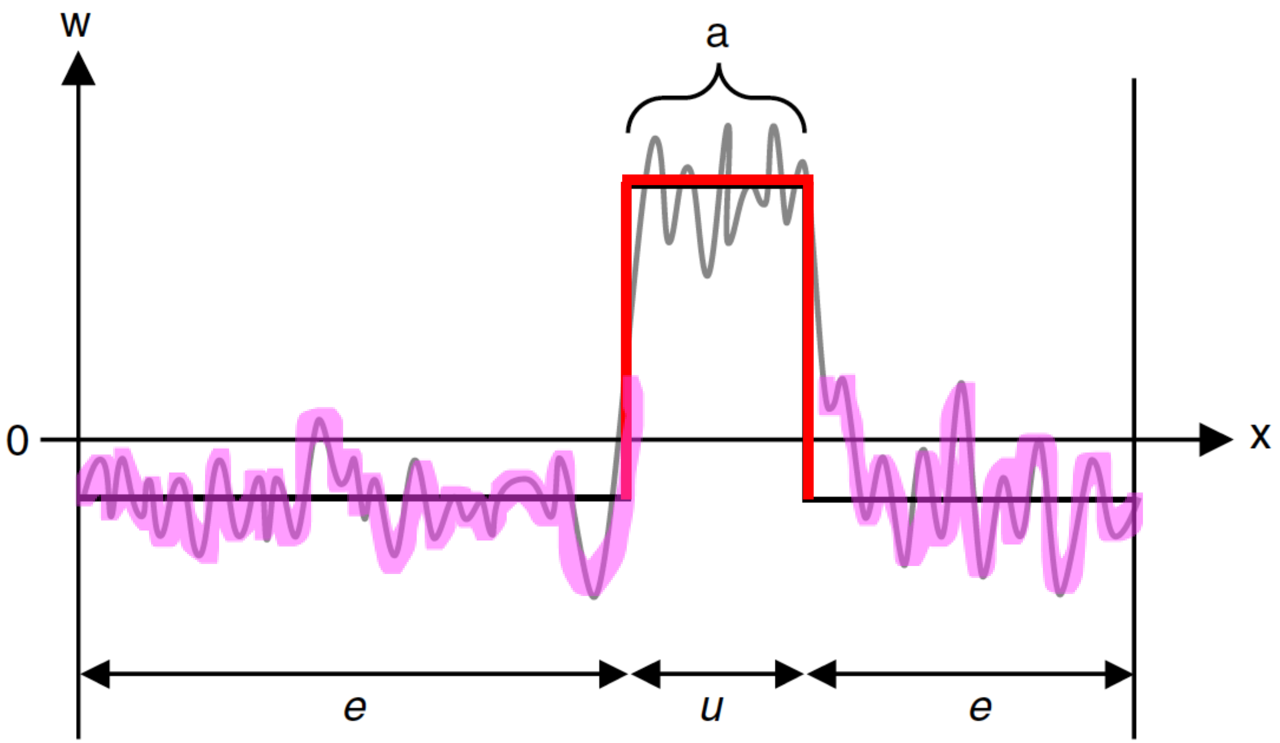
Environmental flux

Mass flux



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Environmental flux

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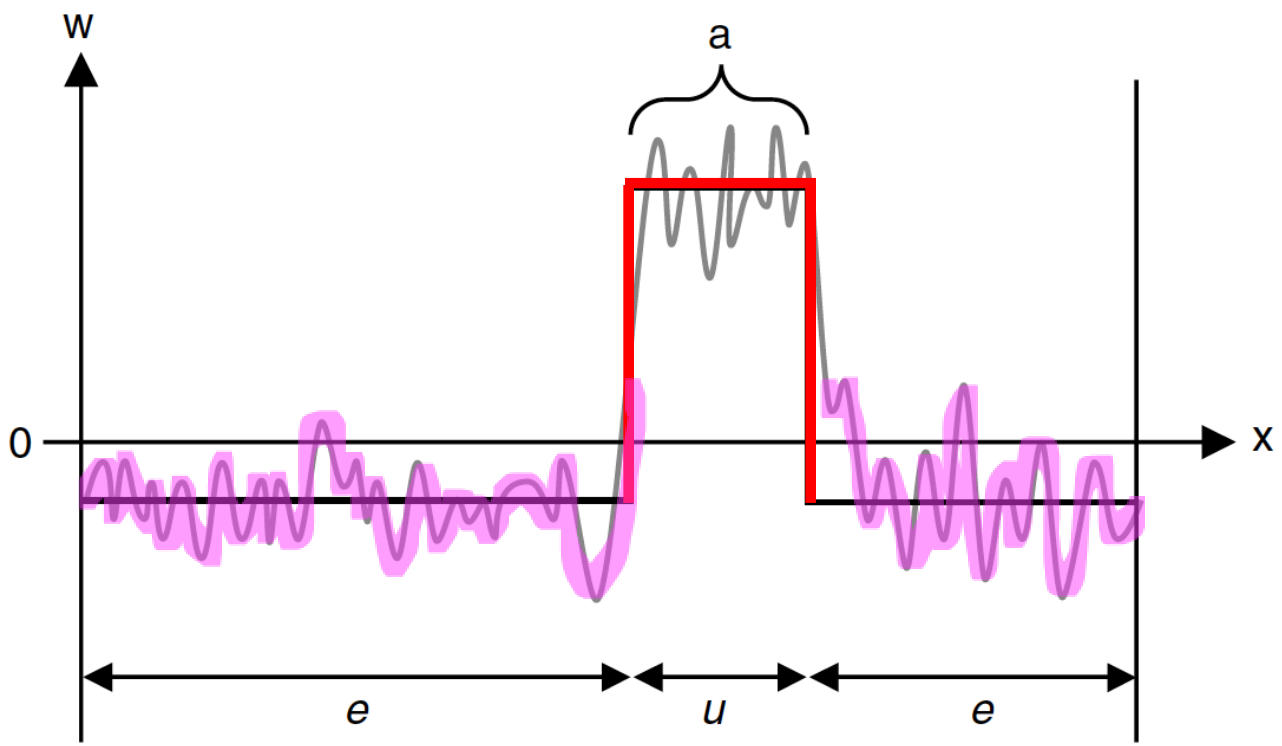

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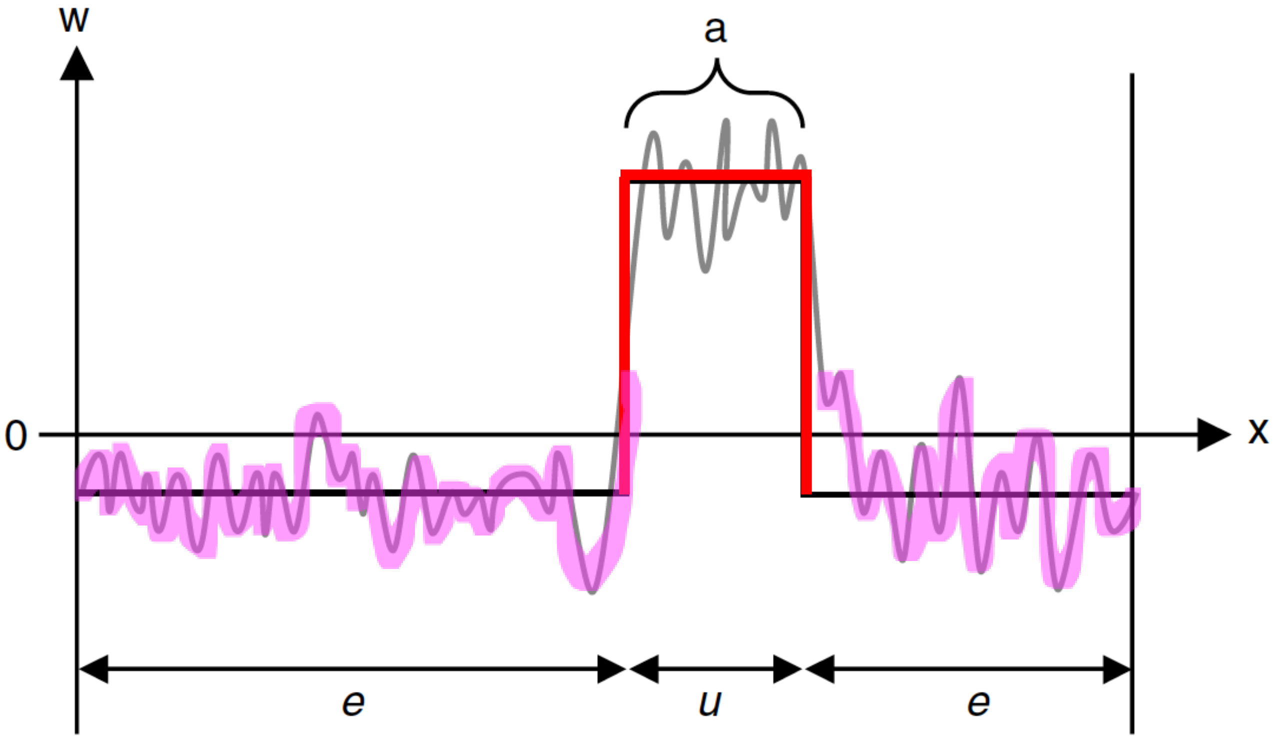
$$M = a(\overline{w}^u - \overline{w})$$

Environmental flux

Mass flux



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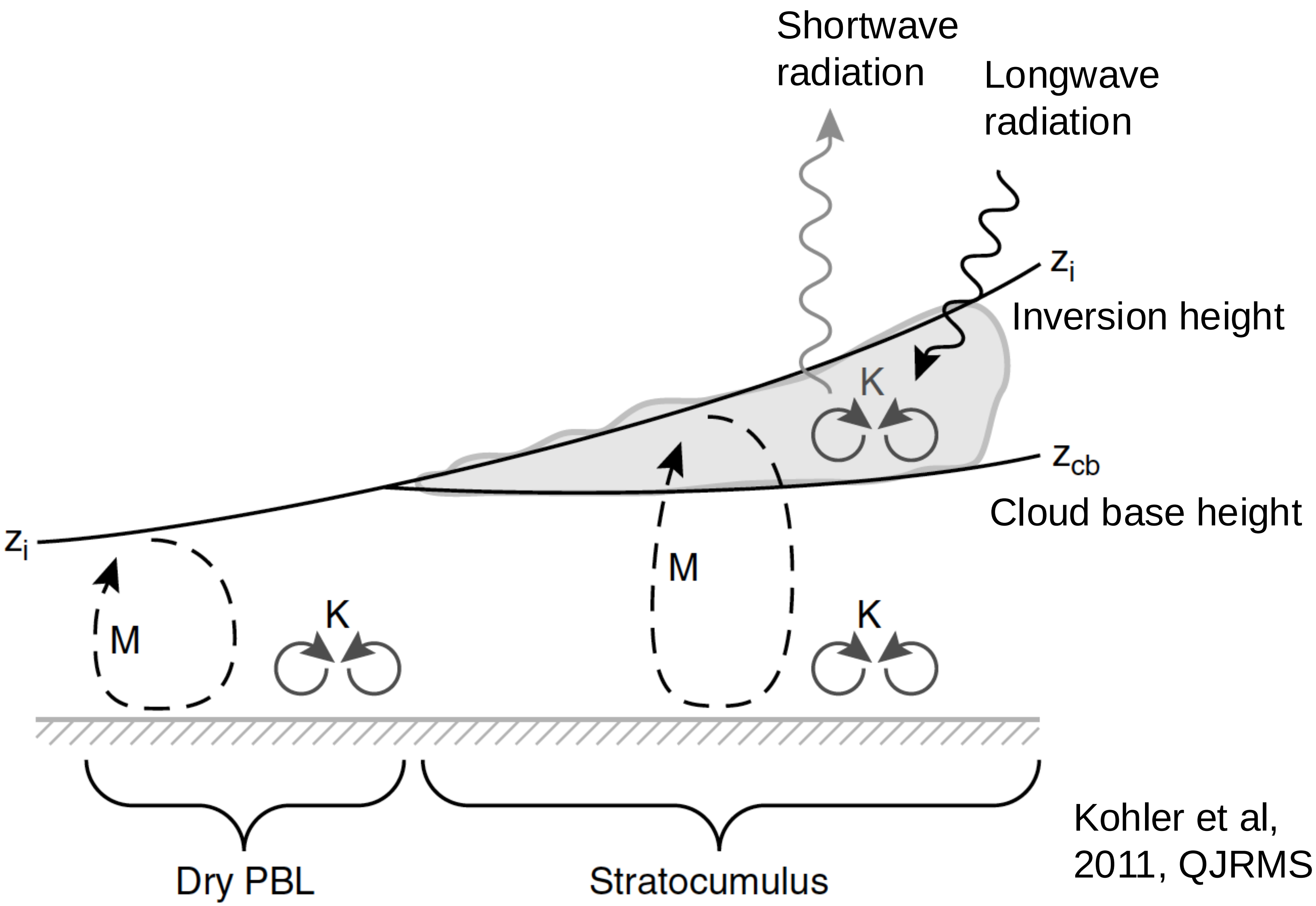
The surface mass flux (M) is initialised at the first model level

The mass flux profile then depends on the inversion height (z_i) or the cloud base height (z_{cb})



Kohler et al, 2011, QJRMS

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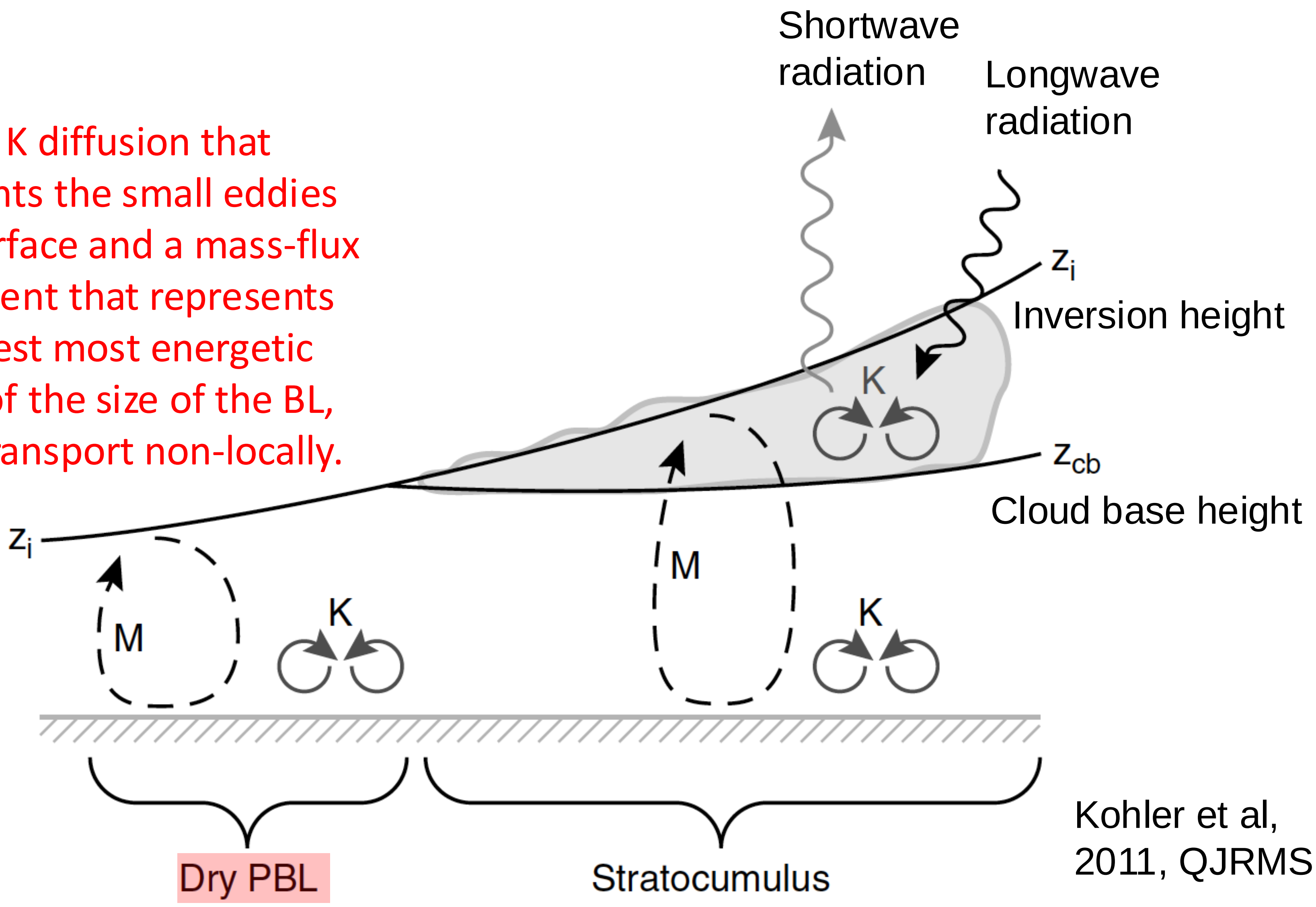

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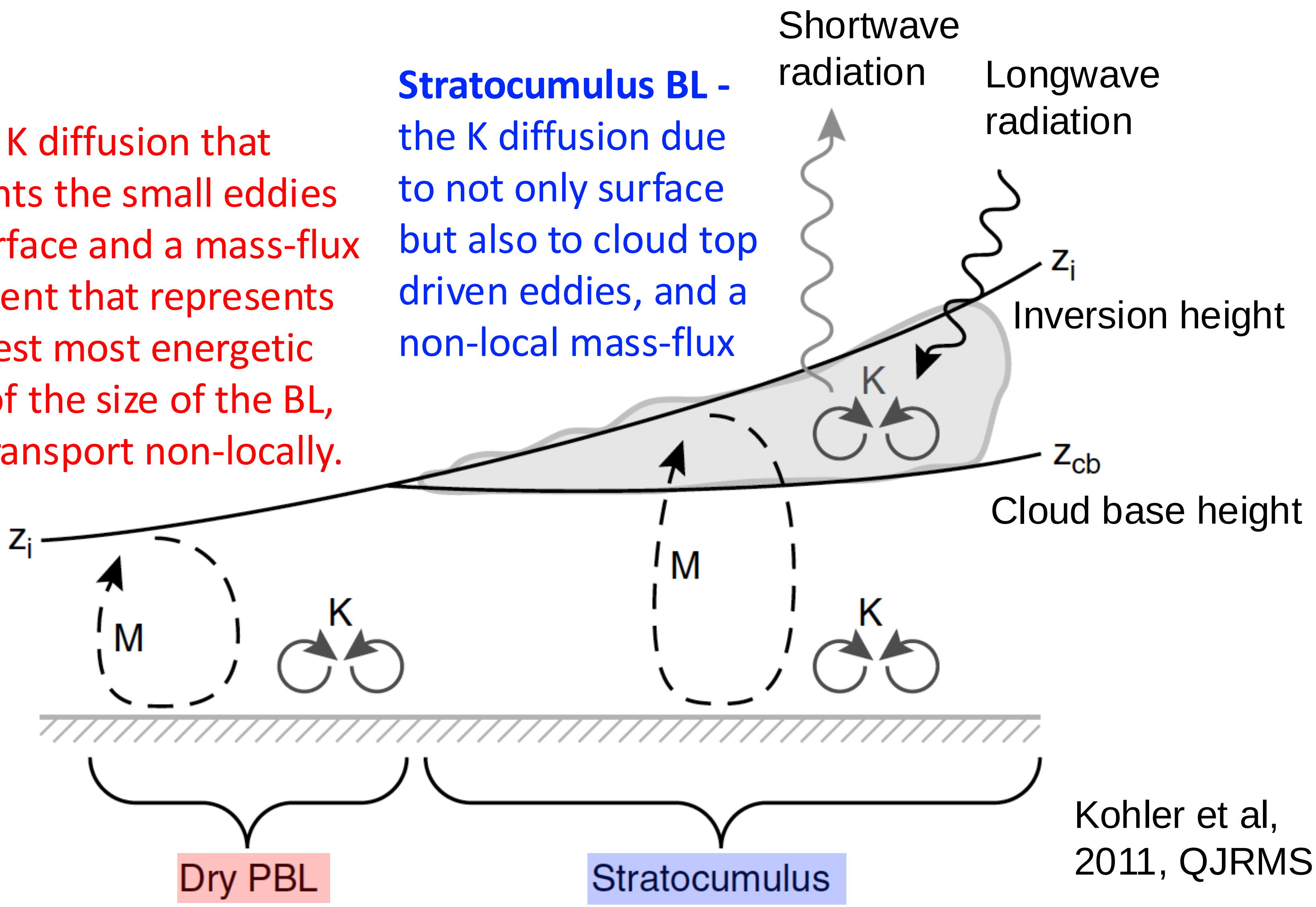
Stratocumulus BL - the K diffusion due to not only surface but also to cloud top driven eddies, and a non-local mass-flux



Kohler et al, 2011, QJRMS

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Description of the current ECMWF IFS scheme

Description of the current IFS scheme

Stable surface layer | Unstable surface layer

Entrainment level

Lowest model level

Surface layer: $\overline{\phi' w'_s} = C_\phi (\overline{\phi_z} - \overline{\phi_s}) \, |\overline{u_z}|$

C_ϕ in surface layer:

$Ri > 0$, Holtslag & Bruin (1988)

$Ri < 0$, Dyer & Hicks (1974)

Description of the current IFS scheme

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Unstable surface layer

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$$K_\phi = \frac{l^2}{\Phi_\phi(\zeta)\Phi_M(\zeta)} \left|\frac{\partial \overline{u}}{\partial z}\right| = l^2 \left|\frac{\partial \overline{u}}{\partial z}\right| f_\phi(Ri)$$

Use the relation

$$Ri = \zeta \frac{\Phi_H(\zeta)}{\Phi_M^2(\zeta)}$$

to convert $\zeta = \frac{z}{L}$ to the gradient Richardson number in the outer layer

Description of the current IFS scheme

K_ϕ above surface:

Dyer & Hicks, $Ri < 0$

Stable surface layer	Unstable surface layer

Outer layer:

$$\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$$

Entrainment level

EDMF:

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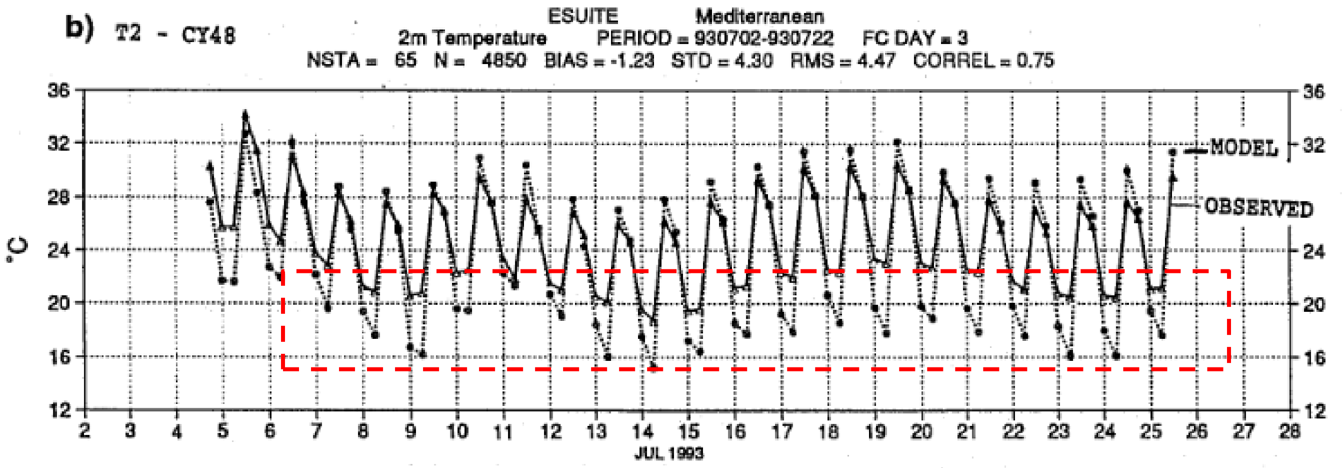
Observations can only take us so far….

Nighttime (stable regime) temperatures were too cold



Beljaars, 1991

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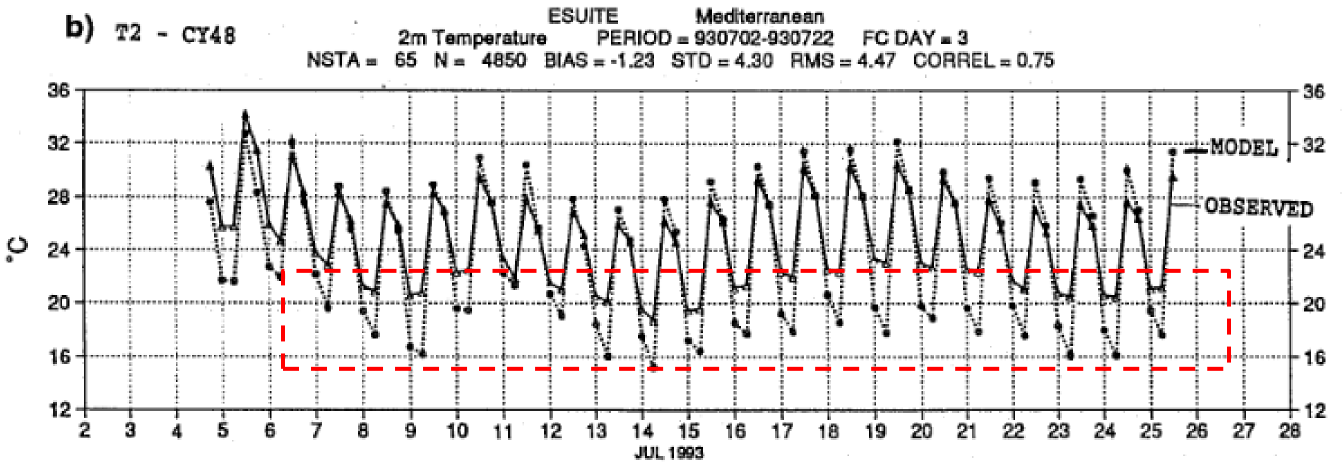
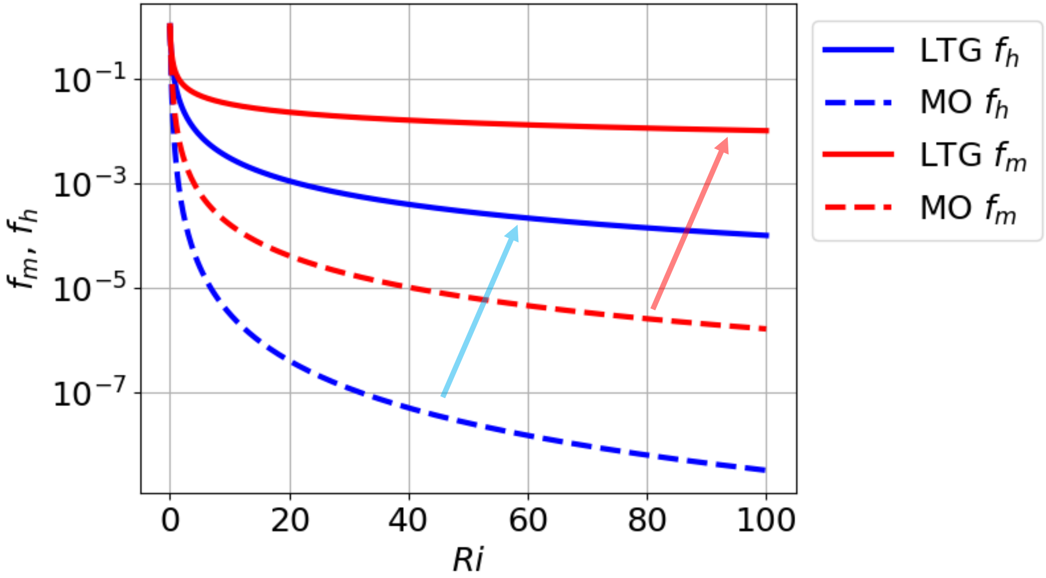


Beljaars, 1991

Mixing was increased in stable BLs



$$\overline{\theta' w'} \sim -l^2 \left|\frac{\partial \bar{u}}{\partial z}\right| \frac{\partial \bar{\theta}}{\partial z} f_H(Ri)$$

$$\overline{u' w'} \sim -l^2 \left|\frac{\partial \bar{u}}{\partial z}\right| \frac{\partial \bar{u}}{\partial z} f_M(Ri)$$

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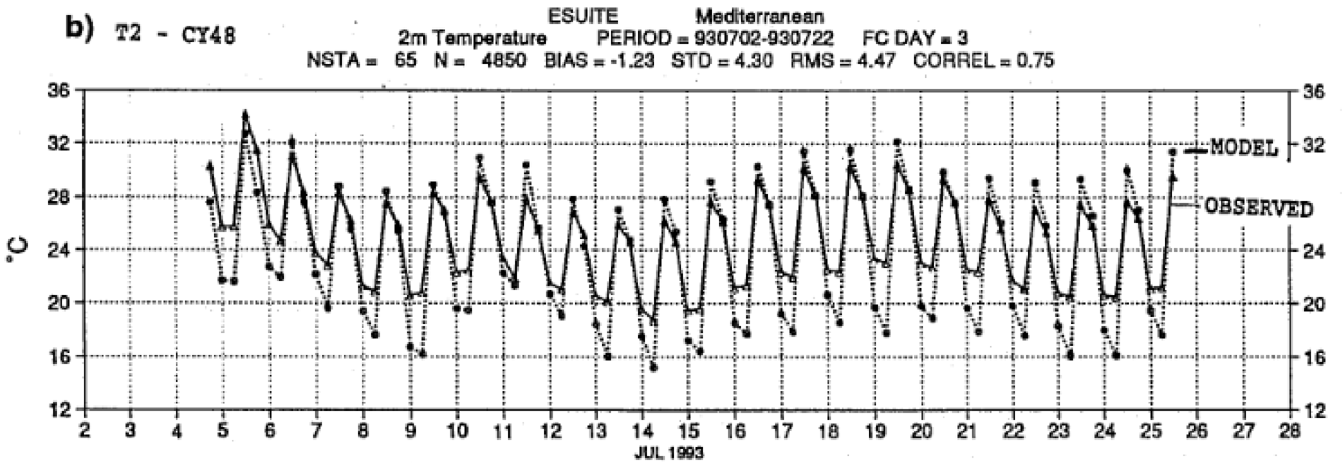
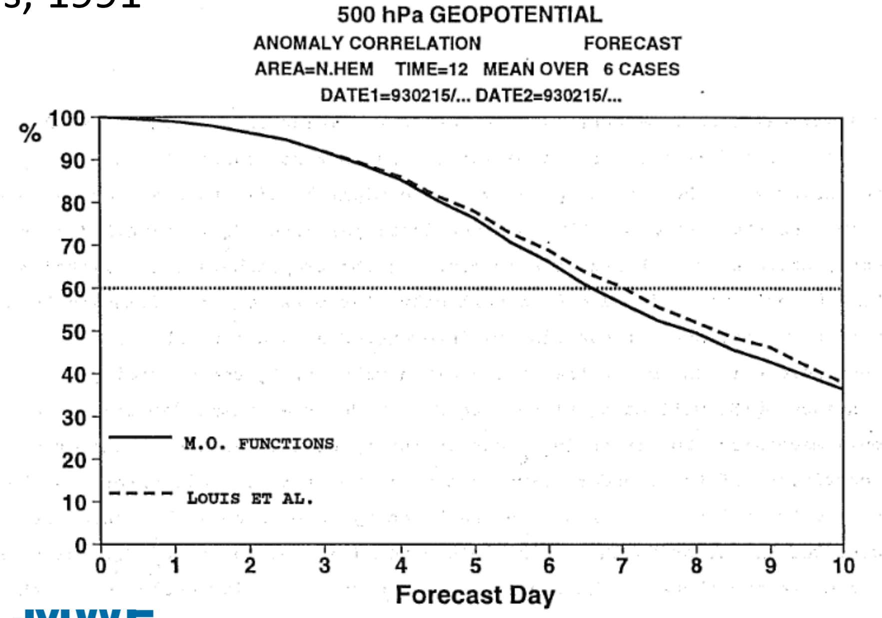


Beljaars, 1991



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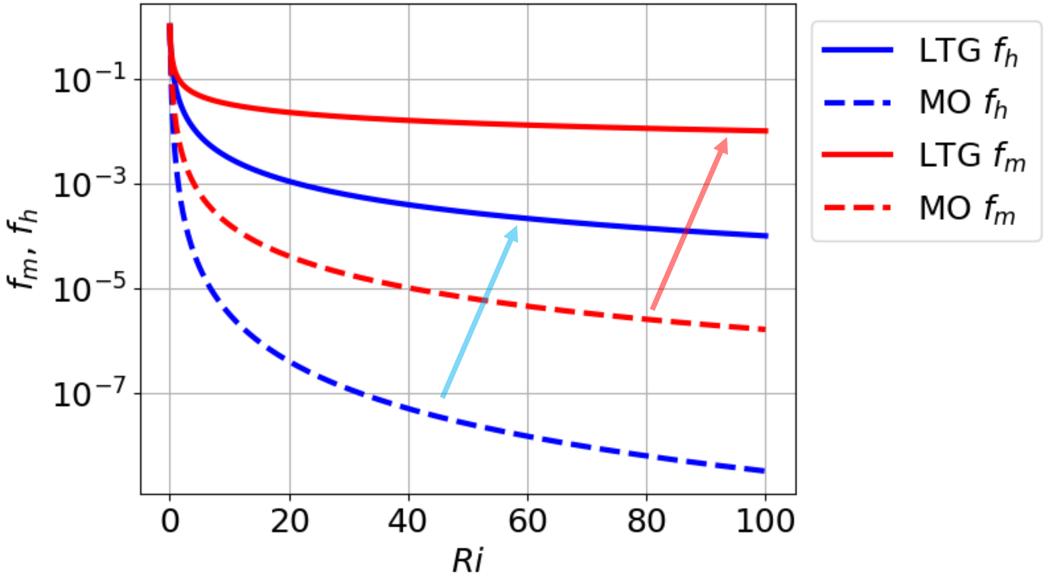

This was a change predominantly motivated by forecast scores, and not direct measurements

$$\overline{\theta' w'} \sim -l^2 \left|\frac{\partial \overline{u}}{\partial z}\right| \frac{\partial \overline{\theta}}{\partial z} f_H(Ri)$$

$$\overline{u' w'} \sim -l^2 \left|\frac{\partial \overline{u}}{\partial z}\right| \frac{\partial \overline{u}}{\partial z} f_M(Ri)$$

Description of the current IFS scheme

'Free' atmosphere: $\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$

K_ϕ above surface:

Dyer & Hicks, $Ri < 0$
Louis (1982), $Ri > 0$

Stable surface layer	Unstable surface layer
	Outer layer: $\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$
	Entrainment level
Outer layer: $\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$	EDMF: $\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z} + M(\overline{\phi}^u - \overline{\phi}^e)$

Lowest model level

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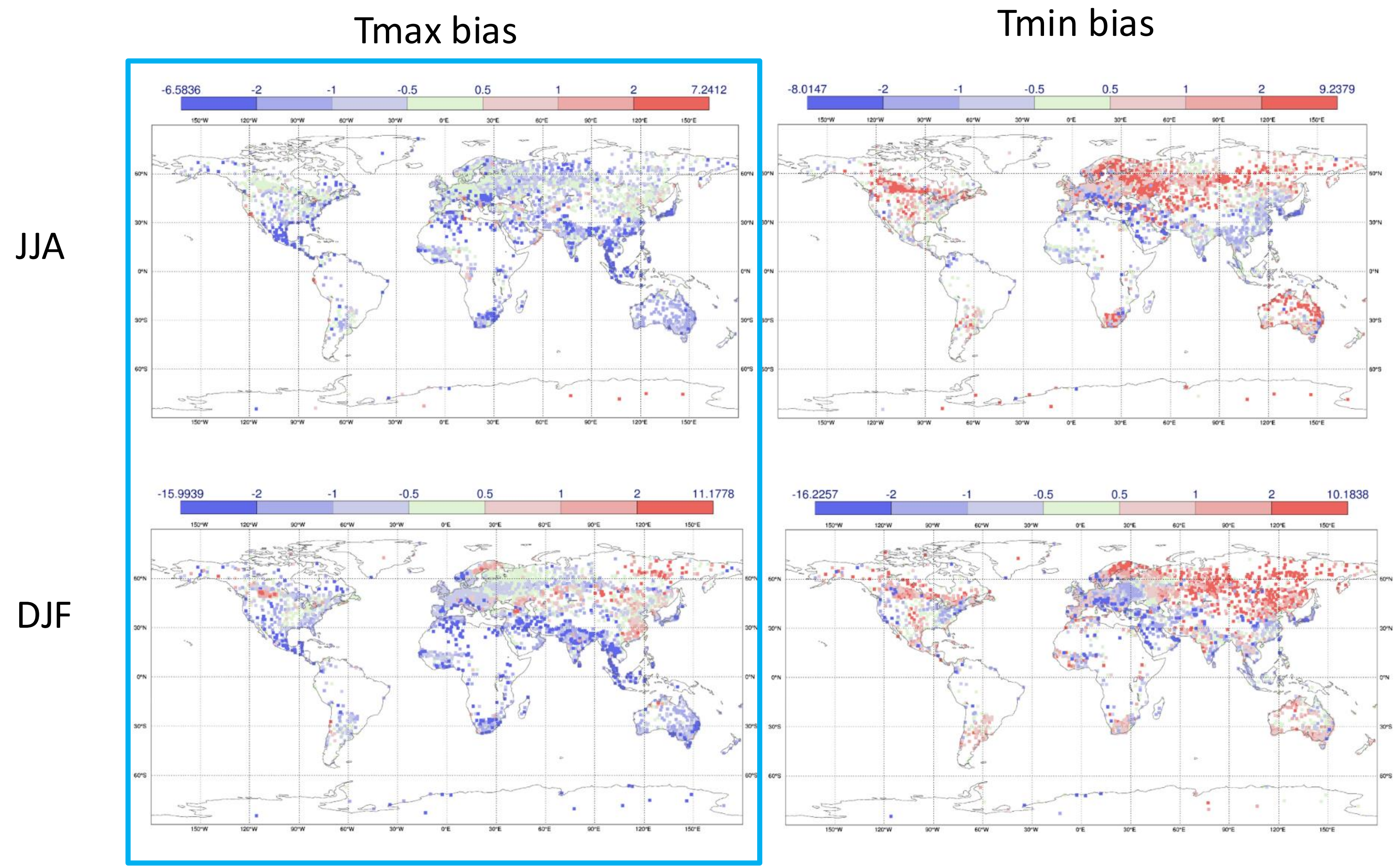
Current near-surface model issues in stable boundary layers

Near surface errors in stable conditions – 2m T



Sandu et al, 2020, ECMWF Tech memo 875

Plots show mean error of maximum (Tmax) and minimum (Tmin) 2m temperatures over 2018/2019 compared with SYNOP observations

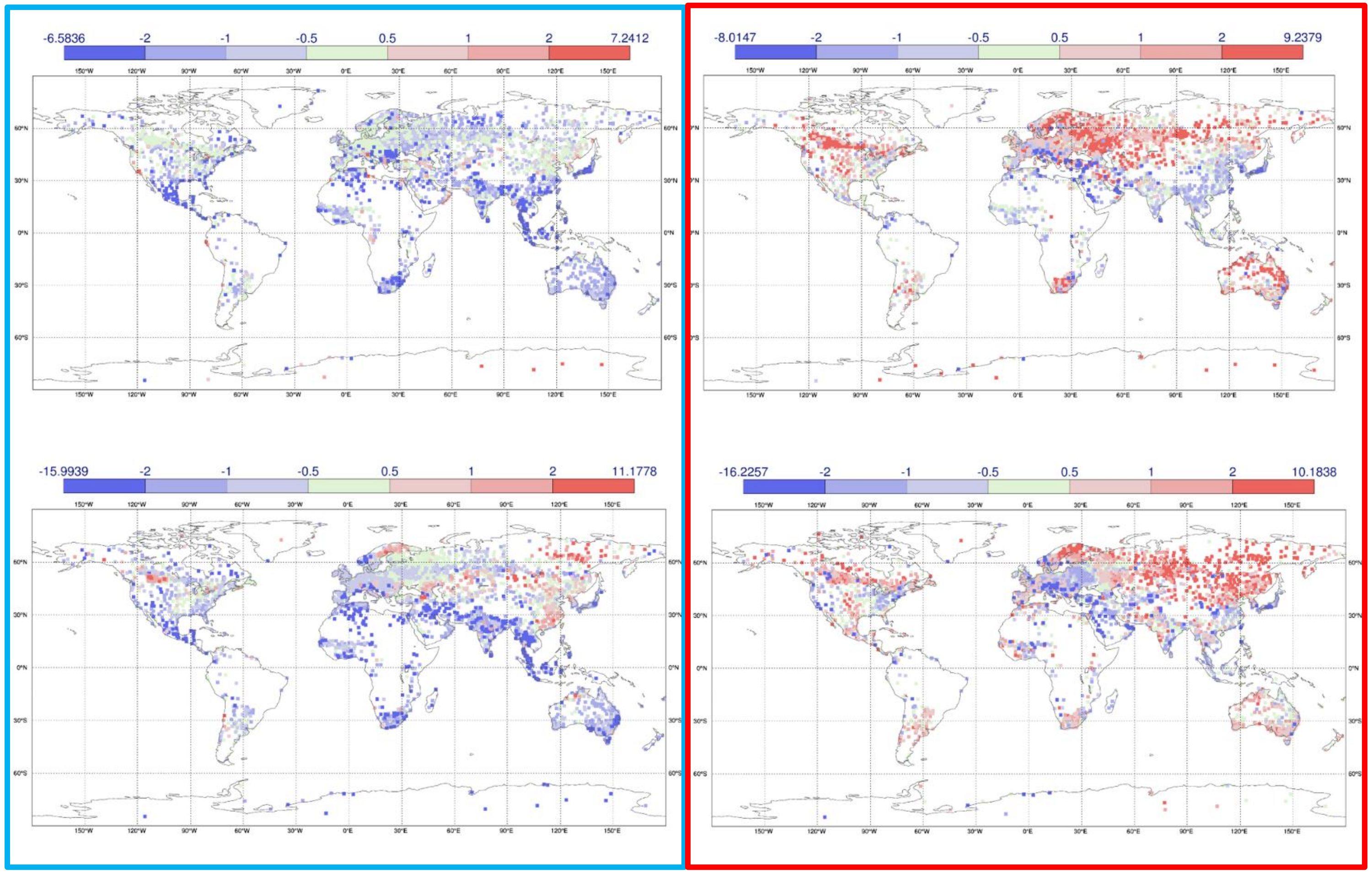
Maximum (daytime) temperatures too cold

Near surface errors in stable conditions – 2m T

Tmax bias | Tmin bias

JJA

DJF



Sandu et al, 2020, ECMWF Tech memo 875

Plots show mean error of maximum (Tmax) and minimum (Tmin) 2m temperatures over 2018/2019 compared with SYNOP observations

Maximum (daytime) temperatures too cold

Minimum (nighttime) temperatures too warm

Mirrors the seasonal cycle

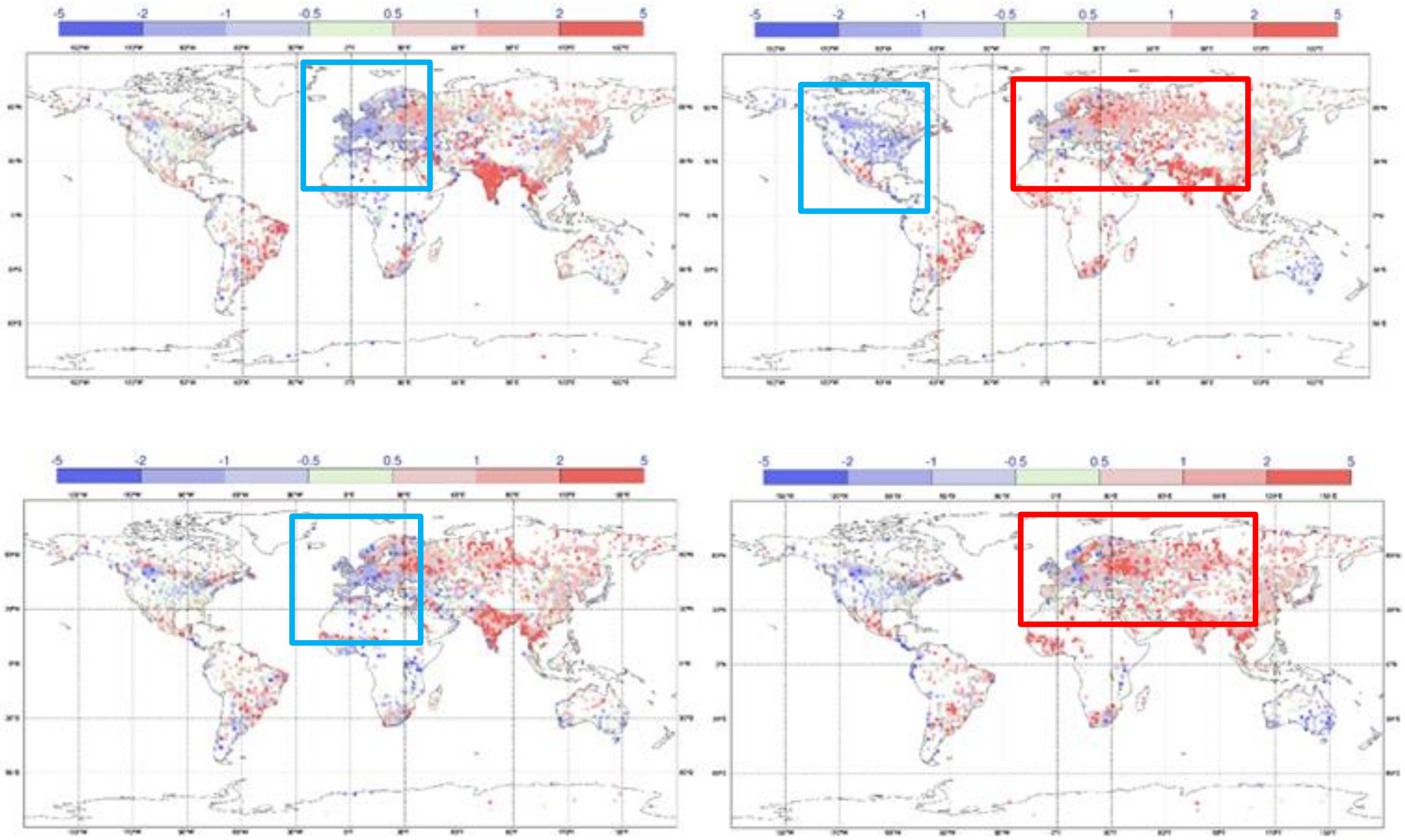
Near surface errors in stable conditions – 10 UV

12 UTC

00 UTC

JJA

DJF



Sandu et al, 2020, ECMWF Tech memo 875

Plots show mean error of 10m wind over 2018/2019 compared with SYNOP observations

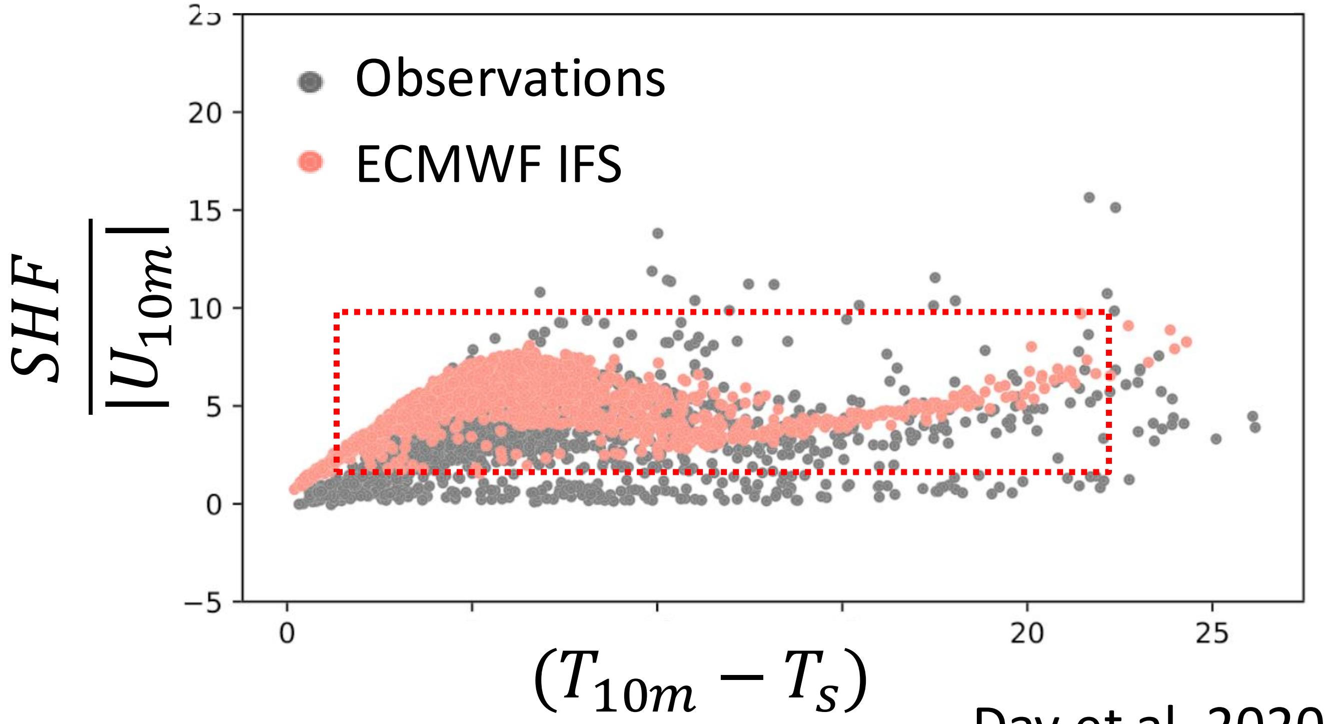
Daytime winds generally too weak

Nighttime / wintertime winds generally too strong

ECMWF

Too much turbulent mixing in stable conditions

Surface sensible heat flux
(Summit, greenland)



Day et al, 2020

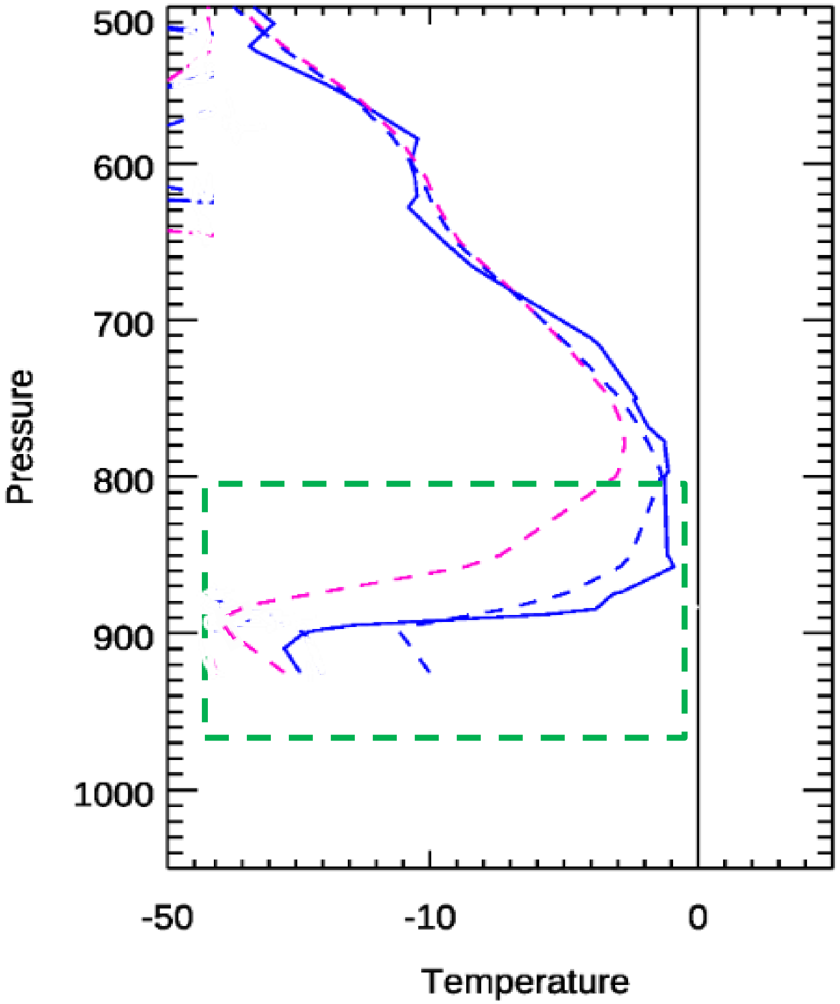
$$SHF = \rho C_H |U_{10m}|(T_{10m} - T_s)$$

Comparison between model and observations suggest too much turbulent mixing in stable conditions

ECMWF

Assimilation of 2m temperatures : Issues in stable conditions

Model comparison
with radiosonde



Edmonton (Canada) radiosonde : Solid Blue
- Strong near-surface inversion

Background model: Dashed blue
- Several degrees too warm

Analysis: Dashed magenta
- Deep increment above inversion

To avoid deep increments:

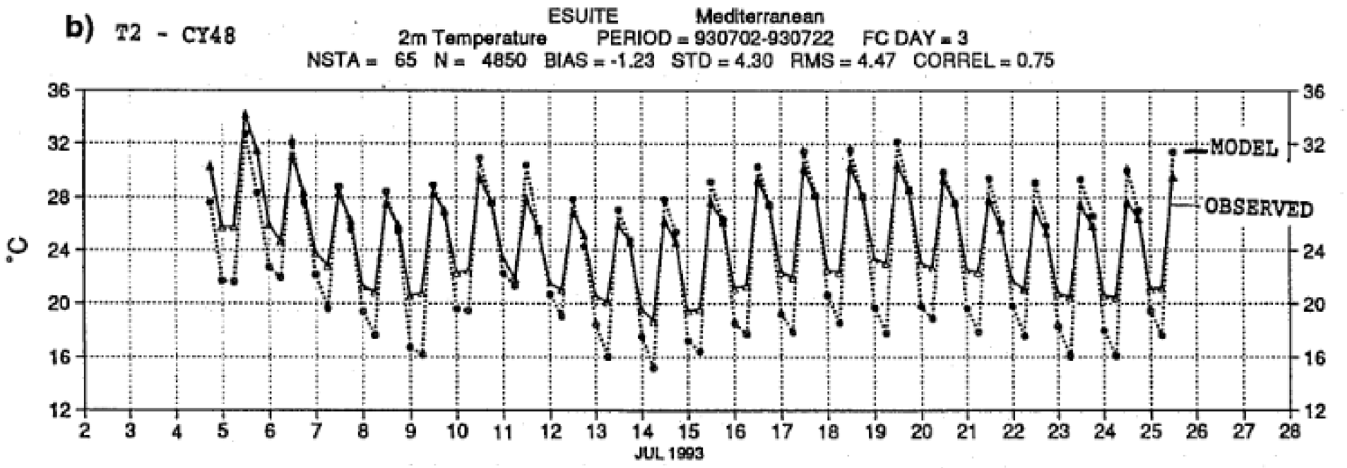
Large differences of the lapse rate adjusted temperature from the background T2m temperature field are given a lower weighting.

Temperature differences of more than 7.5 K are not used.

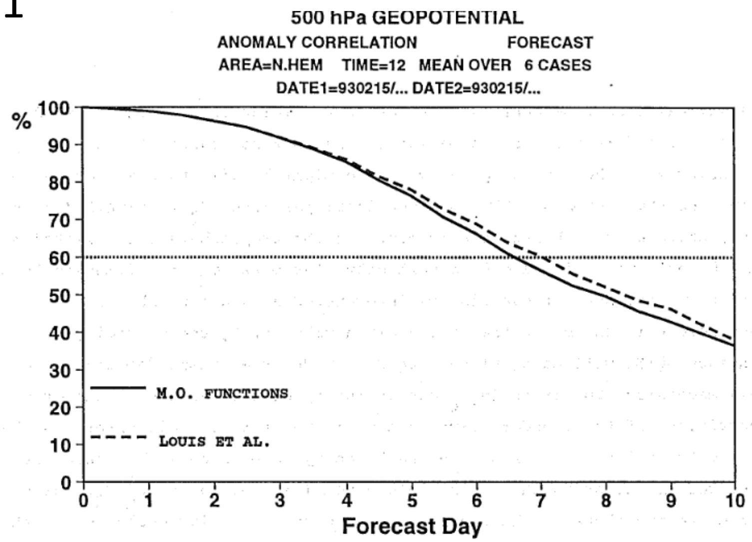
Observations are limited to the first six hours of the 12-hour 4D-Var window to produce more localised increments.

Remember when there was not enough mixing?

Nighttime (stable regime) temperatures were too cold

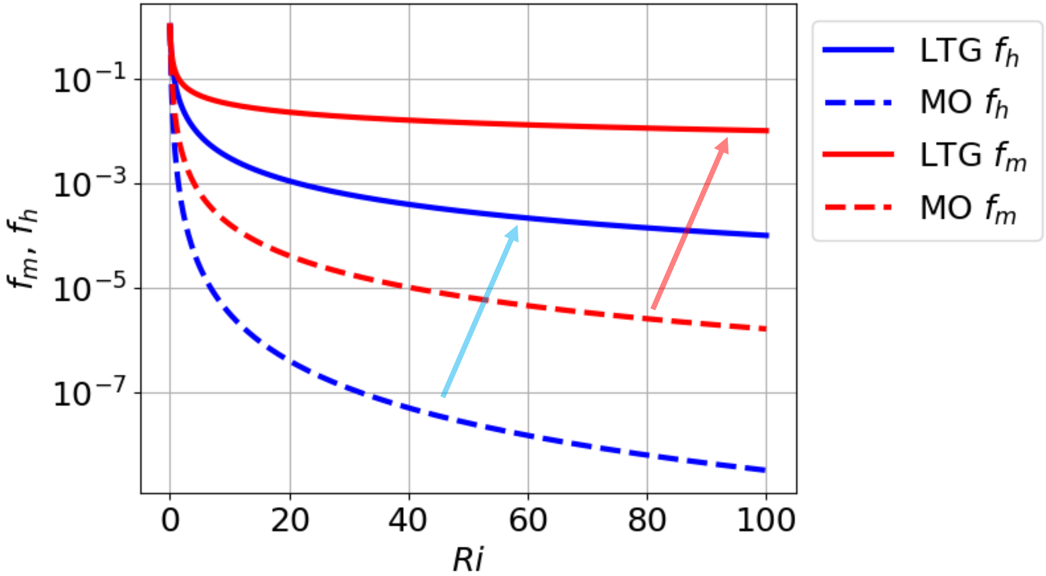


Beljaars, 1991



This was a change predominantly motivated by forecast scores, and not measurement

Mixing was increased in stable BLs



$$\overline{\theta' w'} \sim -l^2 \left|\frac{\partial \bar{u}}{\partial z}\right| \frac{\partial \bar{\theta}}{\partial z} f_H(Ri)$$

$$\overline{u' w'} \sim -l^2 \left|\frac{\partial \bar{u}}{\partial z}\right| \frac{\partial \bar{u}}{\partial z} f_M(Ri)$$

ECMWF

Impact of changing empirical functions

Impact of changing functions

'Free' atmosphere: $\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$

Stable surface layer	Unstable surface layer

Unstable surface layer:

Outer layer:

$$\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$$

Entrainment level

EDMF:

$$\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z} + M(\overline{\phi}^u - \overline{\phi}^e)$$

Stable surface layer:

Outer layer:

$$\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$$

Lowest model level

Surface layer: $\overline{\phi' w'_s} = C_\phi (\overline{\phi_z} - \overline{\phi_s}) \, |\overline{u_z}|$

K_ϕ above surface:

Dyer & Hicks, $Ri < 0$

Louis (1982), $Ri > 0$

C_ϕ in surface layer:

$Ri > 0$, Holtslag & Bruin (1988)

$Ri < 0$, Dyer & Hicks (1974)

Impact of changing functions (outer layer)

'Free' atmosphere: $\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$

Stable surface layer	Unstable surface layer

Unstable surface layer

Outer layer:

$$\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$$

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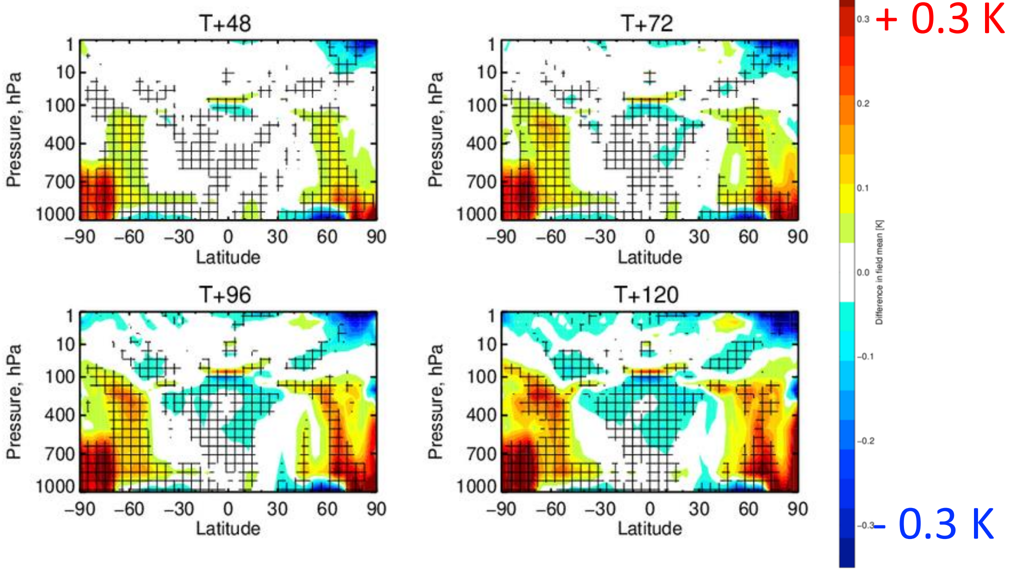
ECMWF

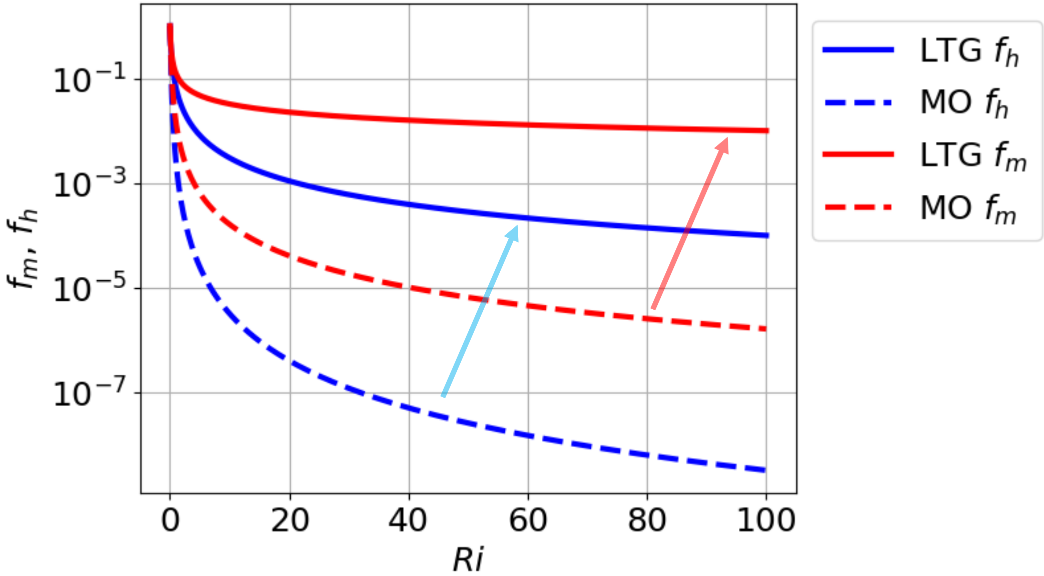
Changing these back has a large impact on the forecast…

Change in T



Cooling near the surface and heating above – less mixing

Mixing reduced again in stable BLs



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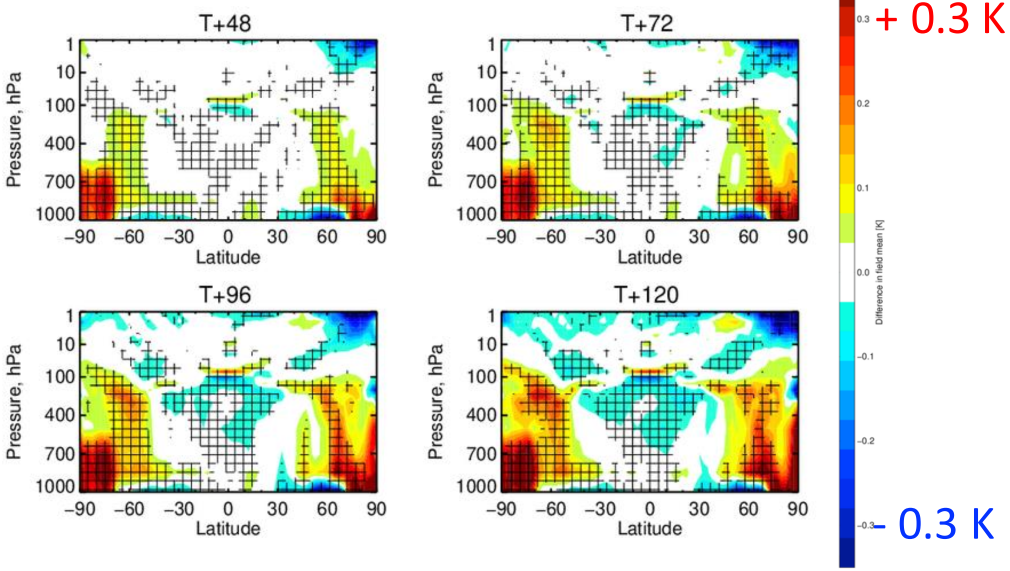

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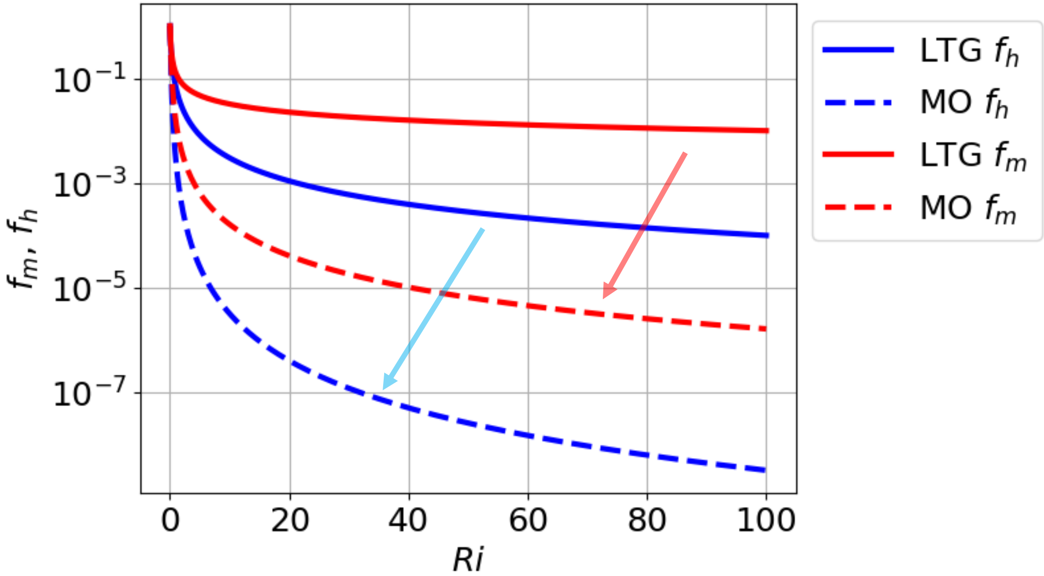

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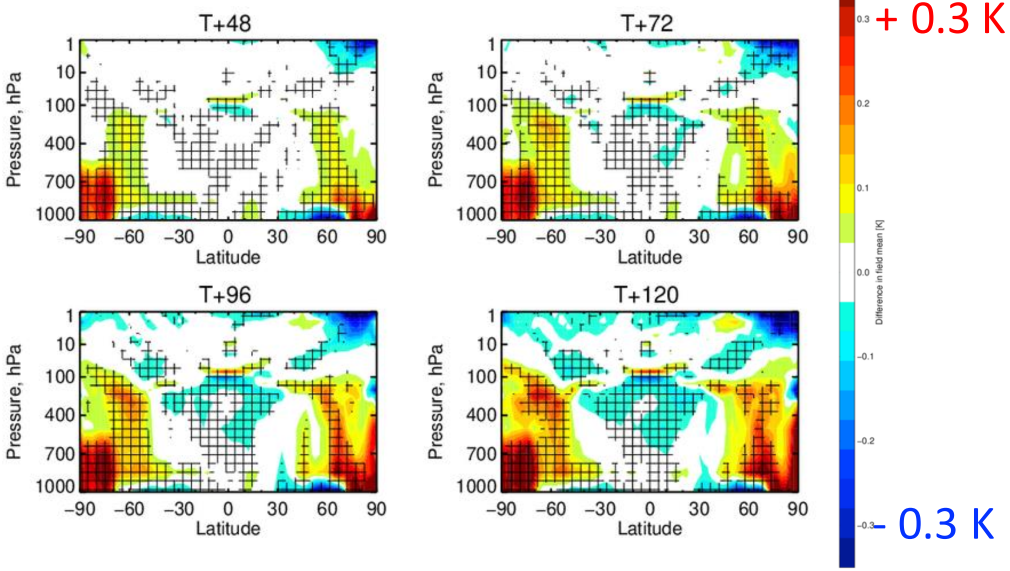
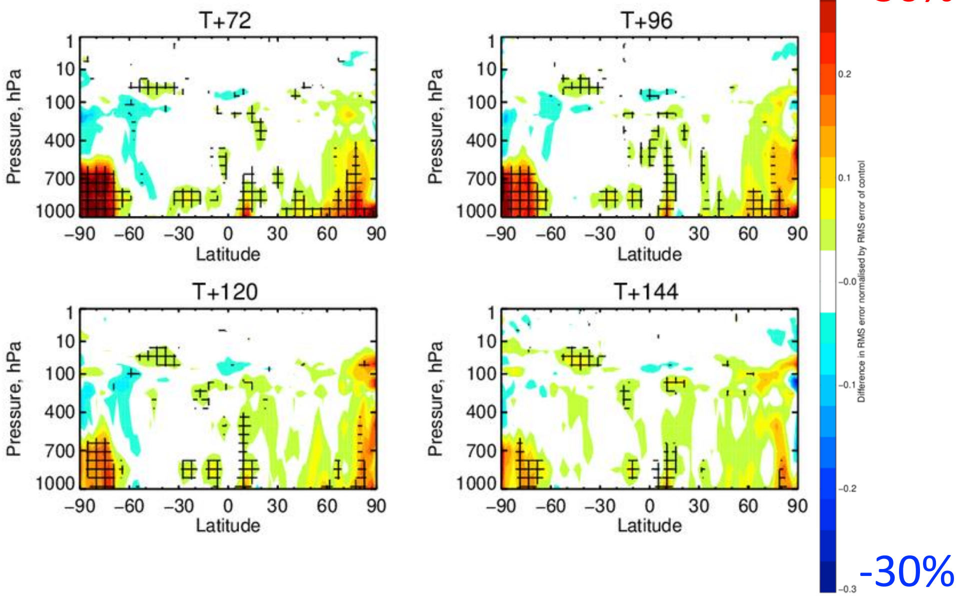


Large degradation of temperature forecast

Change in RMSE of T



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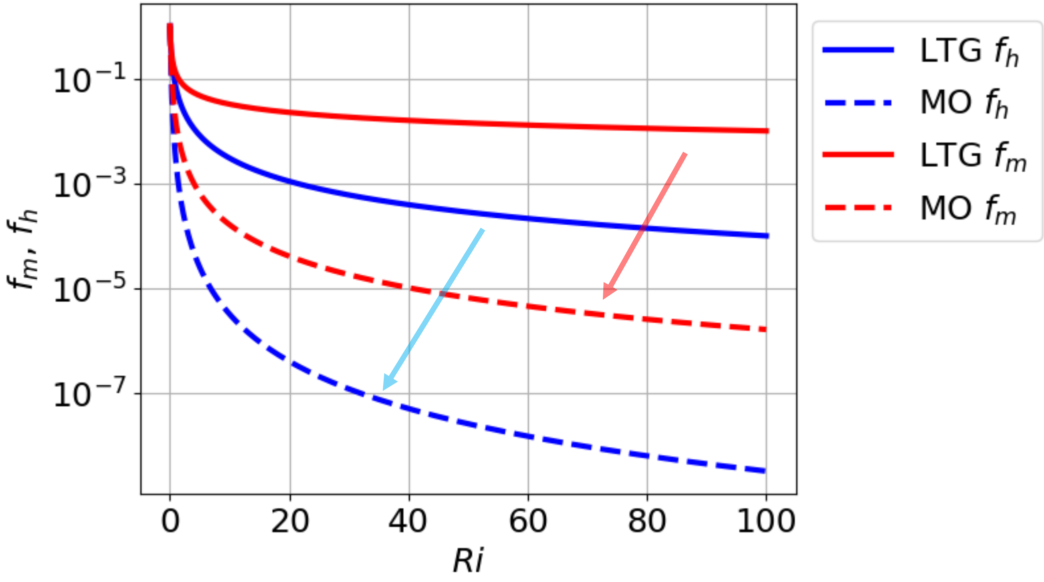

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ECMWF

Empirical stability functions – SHEBA (very stable)

Mix well to form:

Richardson number:

$$Ri = \frac{g}{\theta}\frac{\frac{\partial\theta}{\partial z}}{\frac{\partial U}{\partial z}}$$

Dimensionless wind shear:

$$\Phi_M = \frac{\kappa z}{u_*}\frac{\partial U}{\partial z}$$

Dimensionless temperature gradient:

$$\Phi_H = \frac{\kappa z}{\theta_*}\frac{\partial \theta}{\partial z}$$

Dimensionless height:

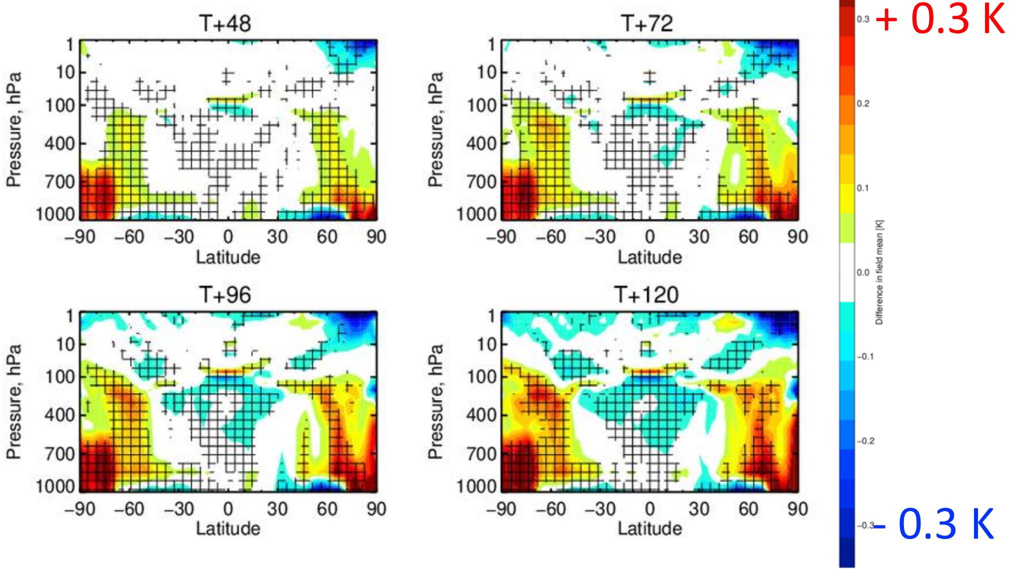
$$\zeta = \frac{z}{L} = z\frac{\kappa g\overline{\theta' w'}}{\theta u_*^3}$$

ECMWF

Changing these back has a large impact on the forecast…

Cooling near the surface and heating above – less mixing

Change in T



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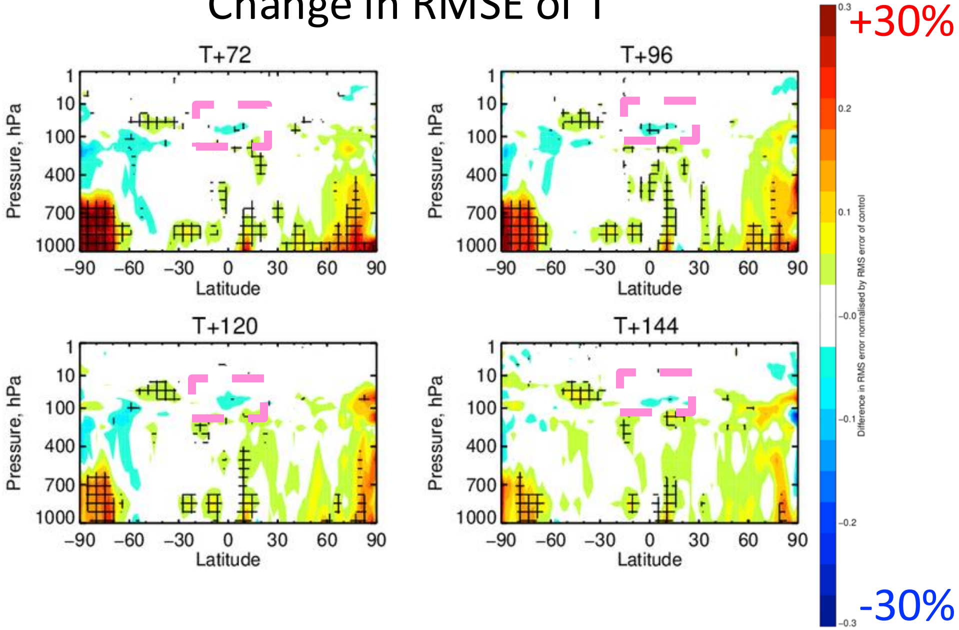
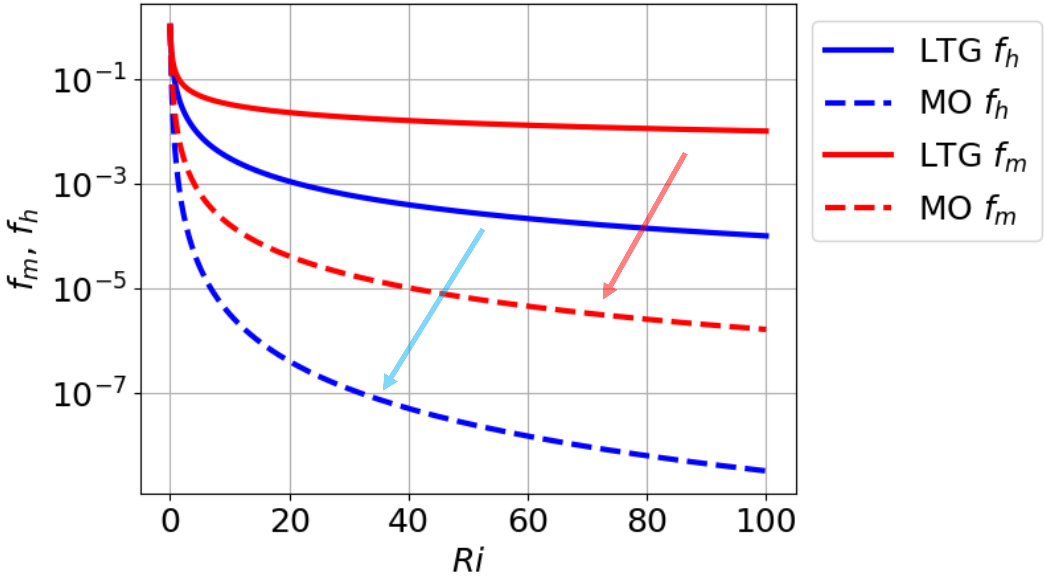


Mixing reduced again in stable BLs



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ECMWF

Impact of changing functions (stratosphere)

'Free' atmosphere: $\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$

Stable surface layer	Unstable surface layer
Outer layer: $\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$	Outer layer: $\overline{\phi' w'} = -K_\phi \frac{\partial \phi}{\partial z}$
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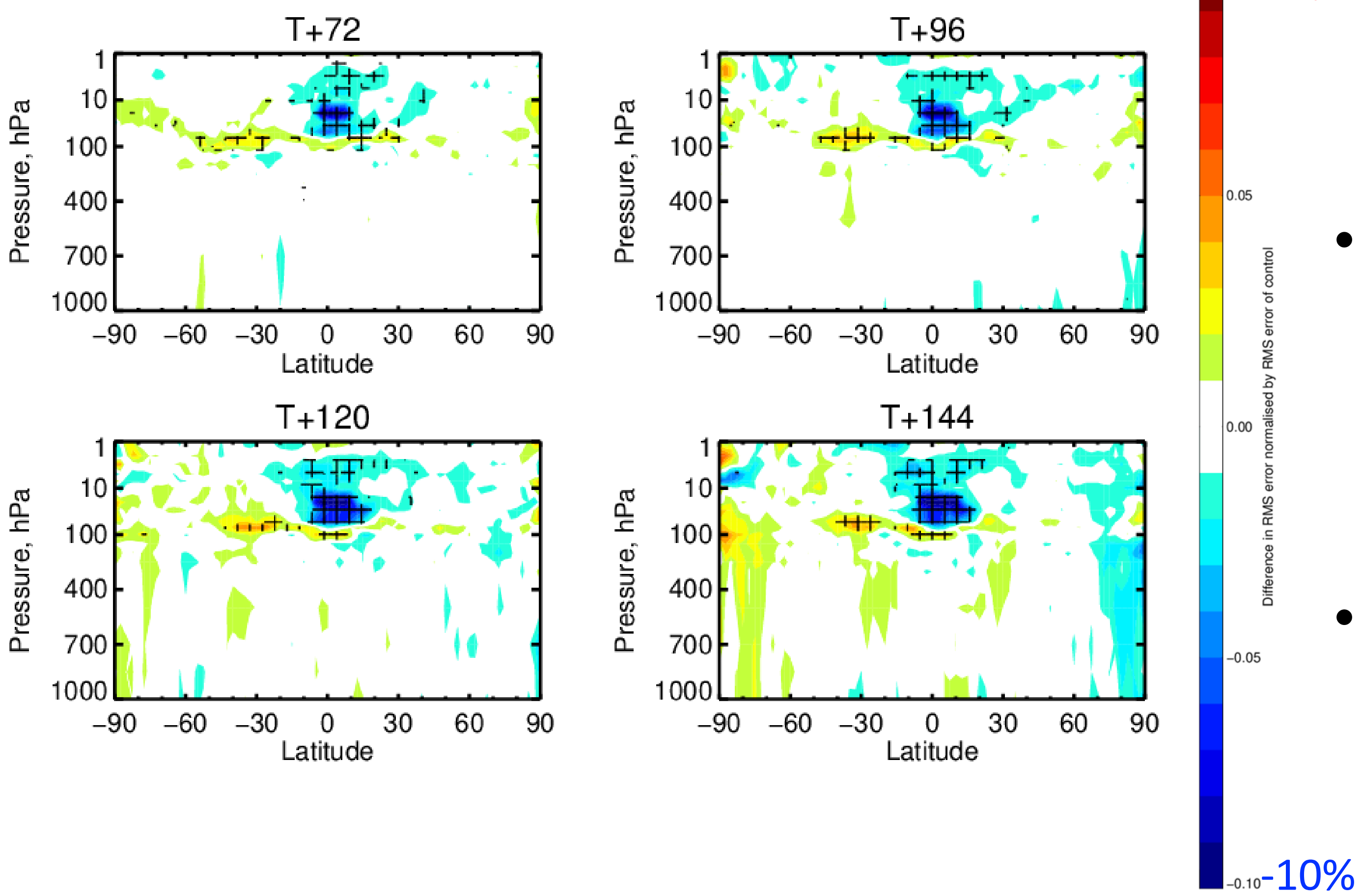
ECMWF

Impact of changing functions (stratosphere)

Change in RMSE of vector Winds

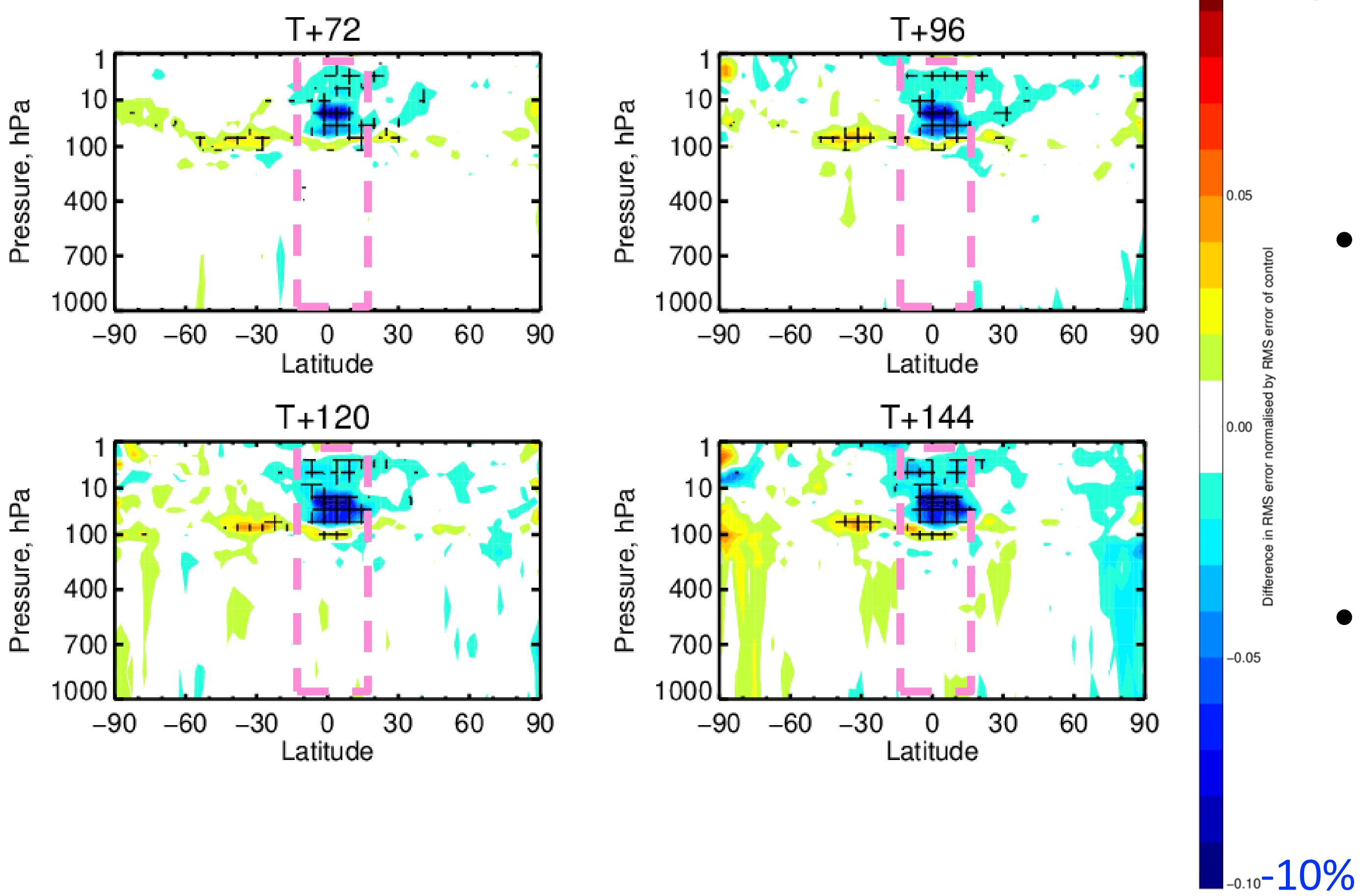


- Typically, the same exchange coefficients are used in the stratosphere as in the outer / mixed layer
- There is little constraint on the exchange coefficients in the stratosphere, where the flow is very stable
- Reducing diffusion in the stratosphere (above the tropopause) leads to improved winds and a better Quasi-biennal Oscillation of the winds in the tropics

ECMWF

Impact of changing functions (stratosphere)

Change in RMSE of vector Winds



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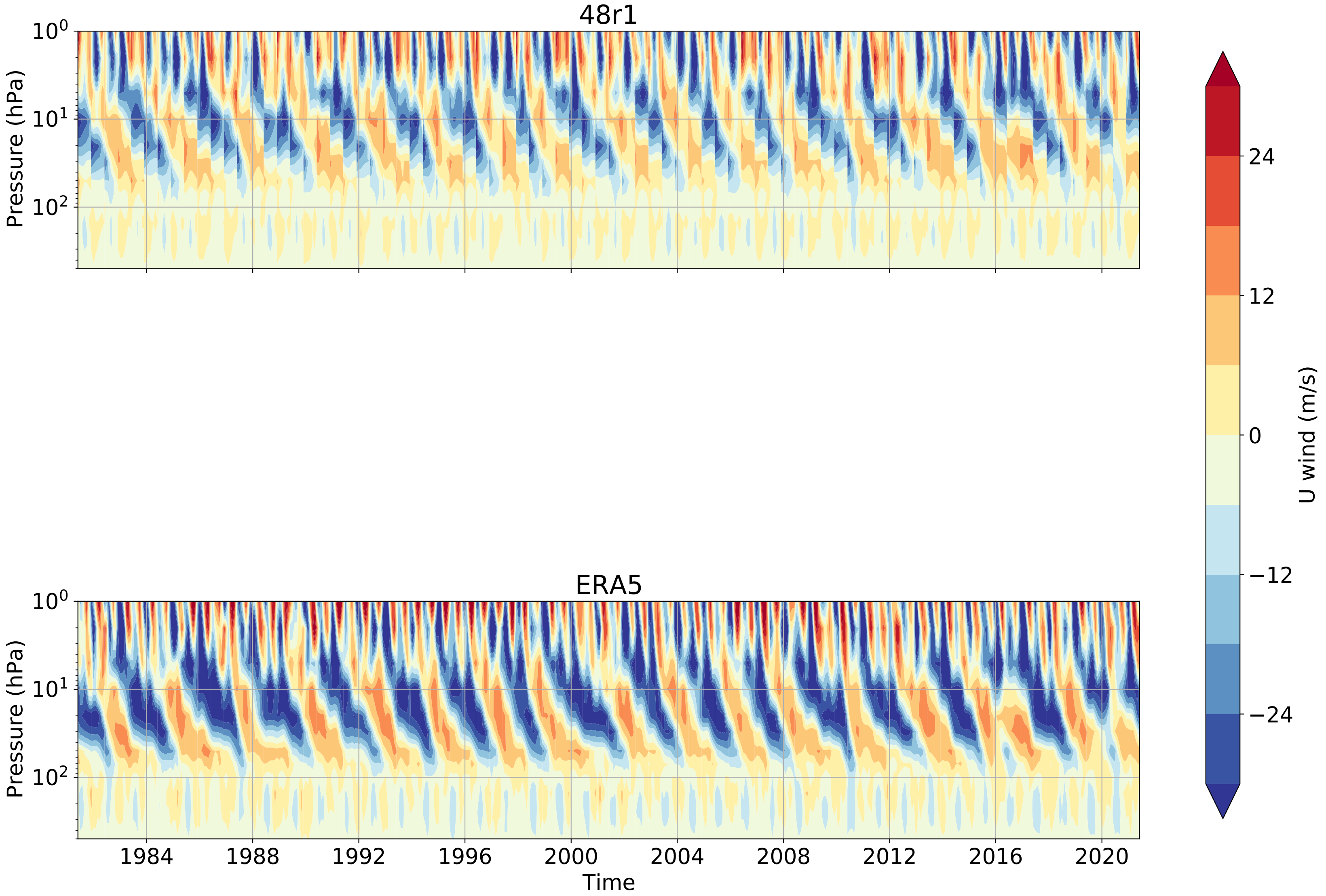
ECMWF

Turbulent diffusion in the stratosphere

Zonal winds averaged between 5S – 5N

Seasonal hindcasts run with the ECMWF IFS, 7 months long

The Quasi-biennial Oscillation (QBO) has too weak amplitude and does not descend far enough



ECMWF

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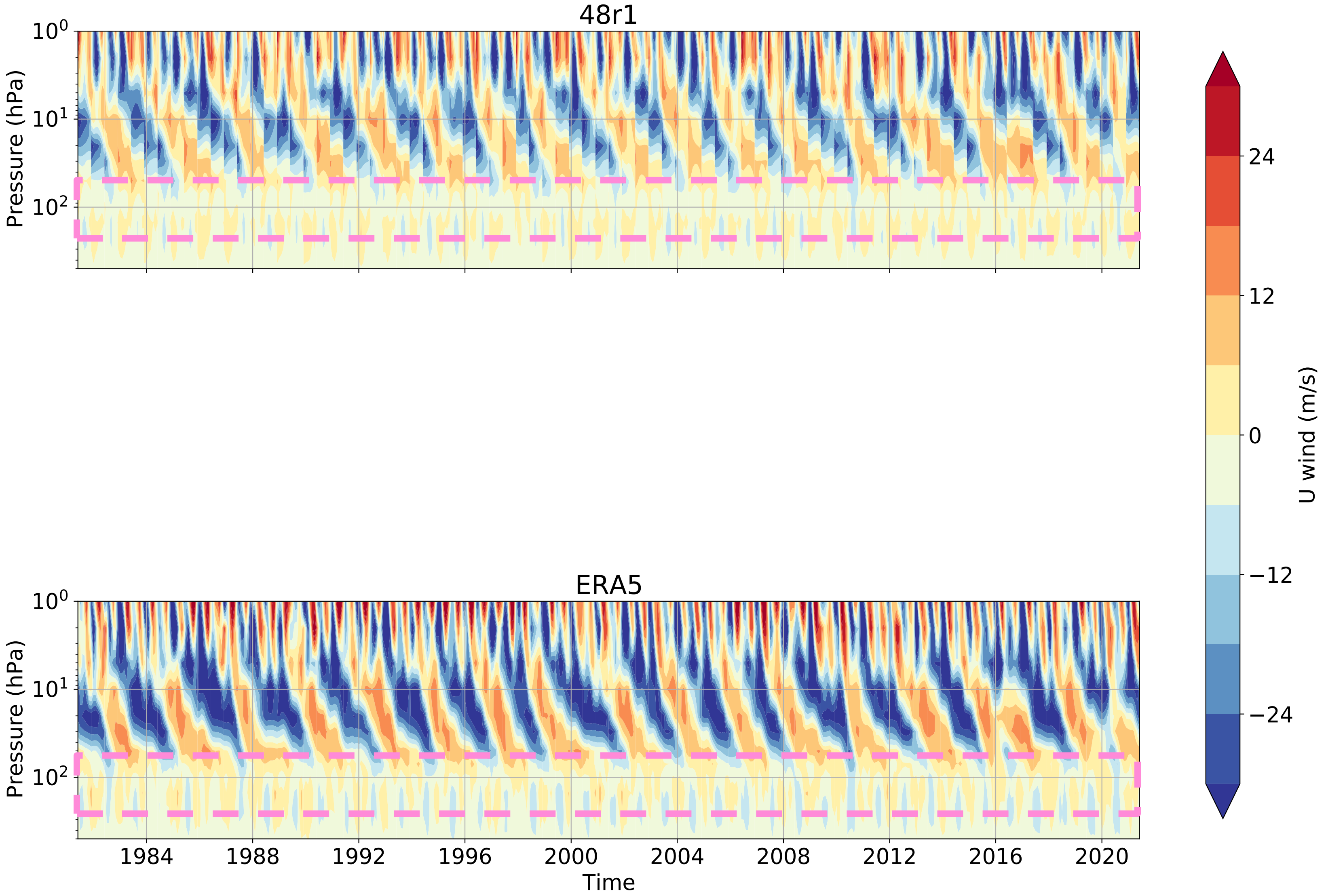

ECMWF

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The Quasi-biennial Oscillation (QBO) has too weak amplitude and does not descend far enough

Reducing vertical diffusion in the stratosphere improves the QBO amplitude and slightly improves its descent

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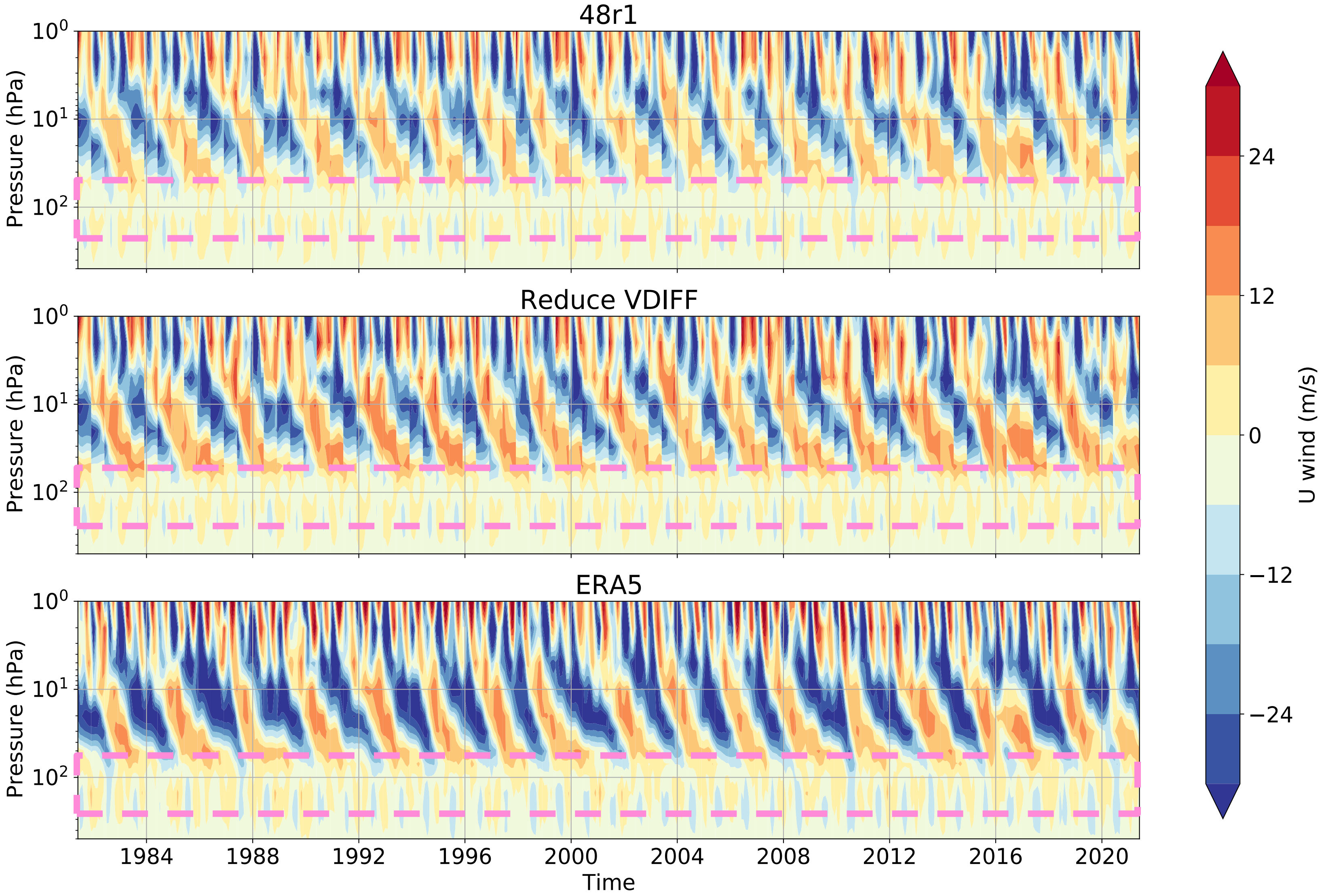

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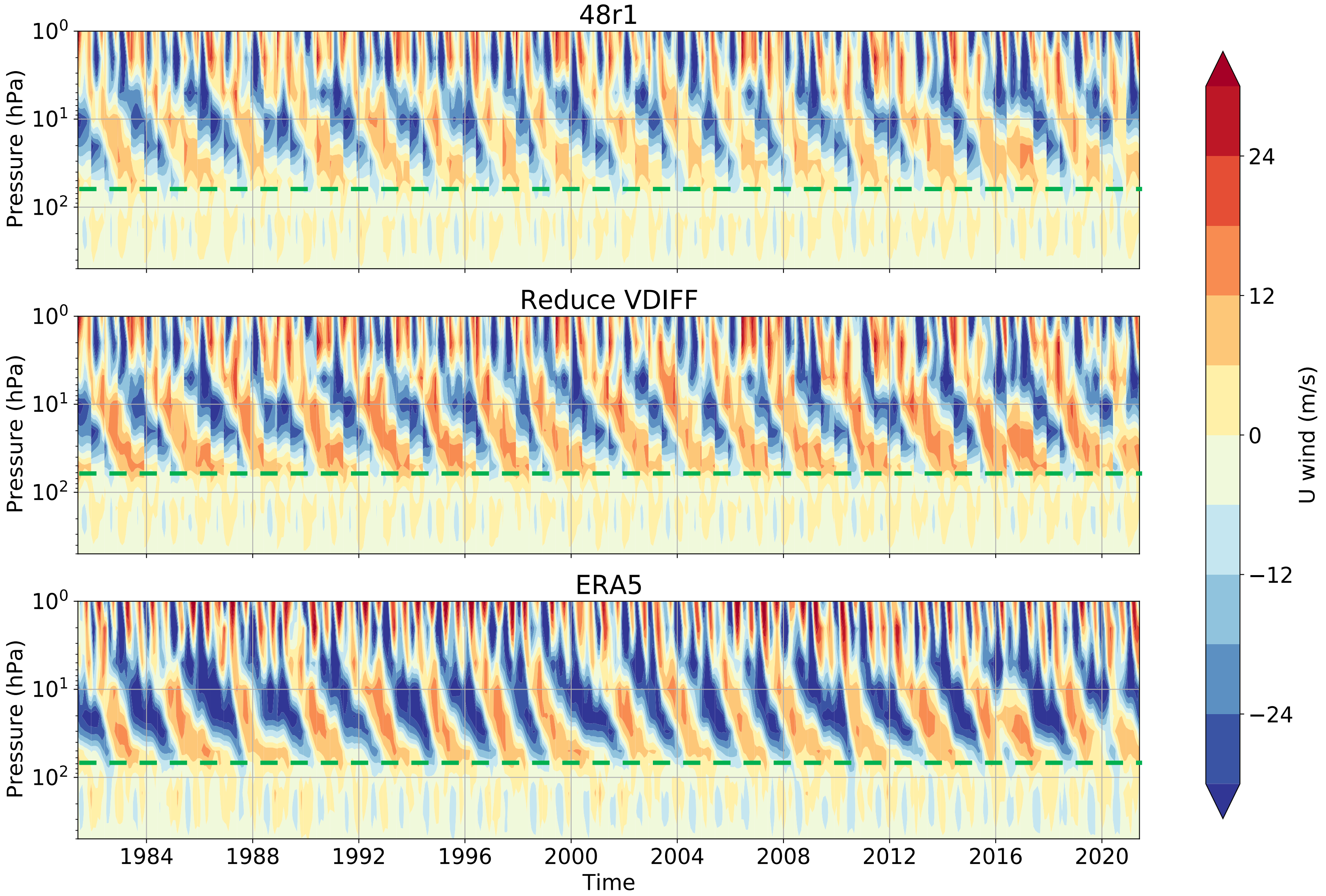
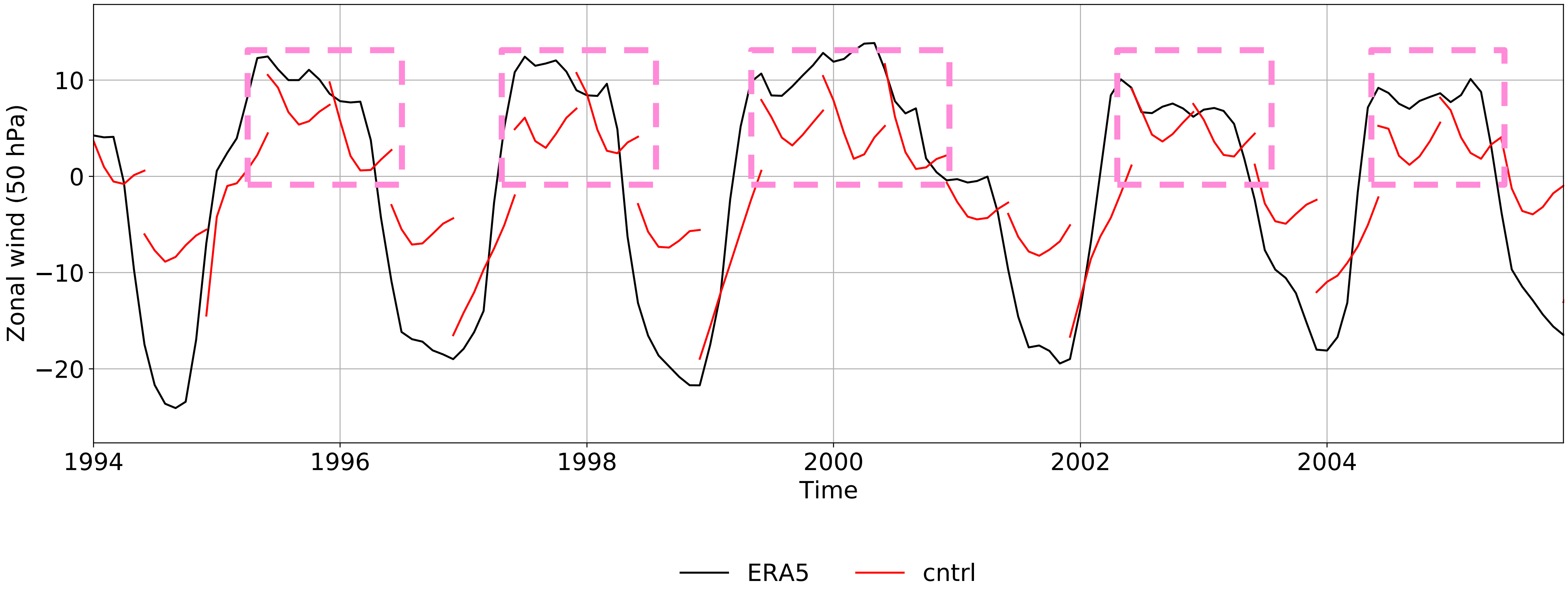


ECMWF

Turbulent diffusion in the stratosphere

Current model has too weak winds in the QBO positive phase

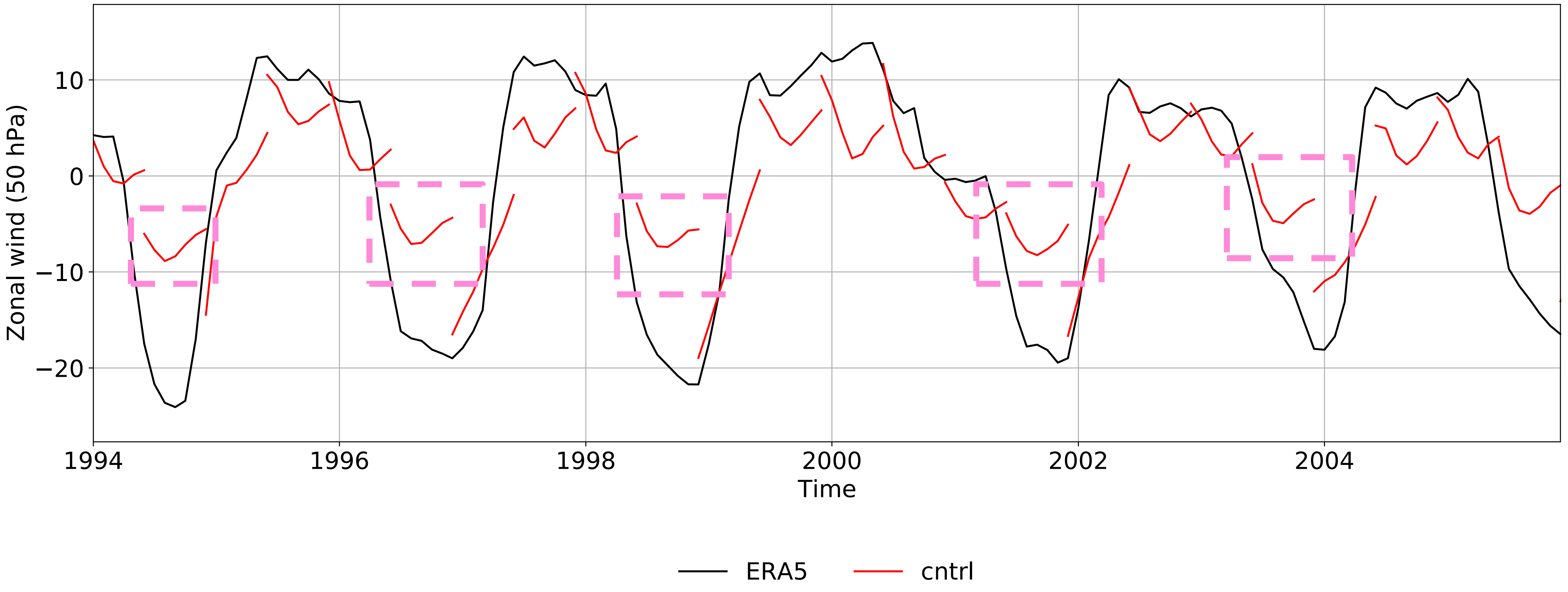


Plot shows 50 hPa zonal winds averaged between 5S – 5N

Seasonal hindcasts run with the ECMWF IFS, 7 months long

Turbulent diffusion in the stratosphere

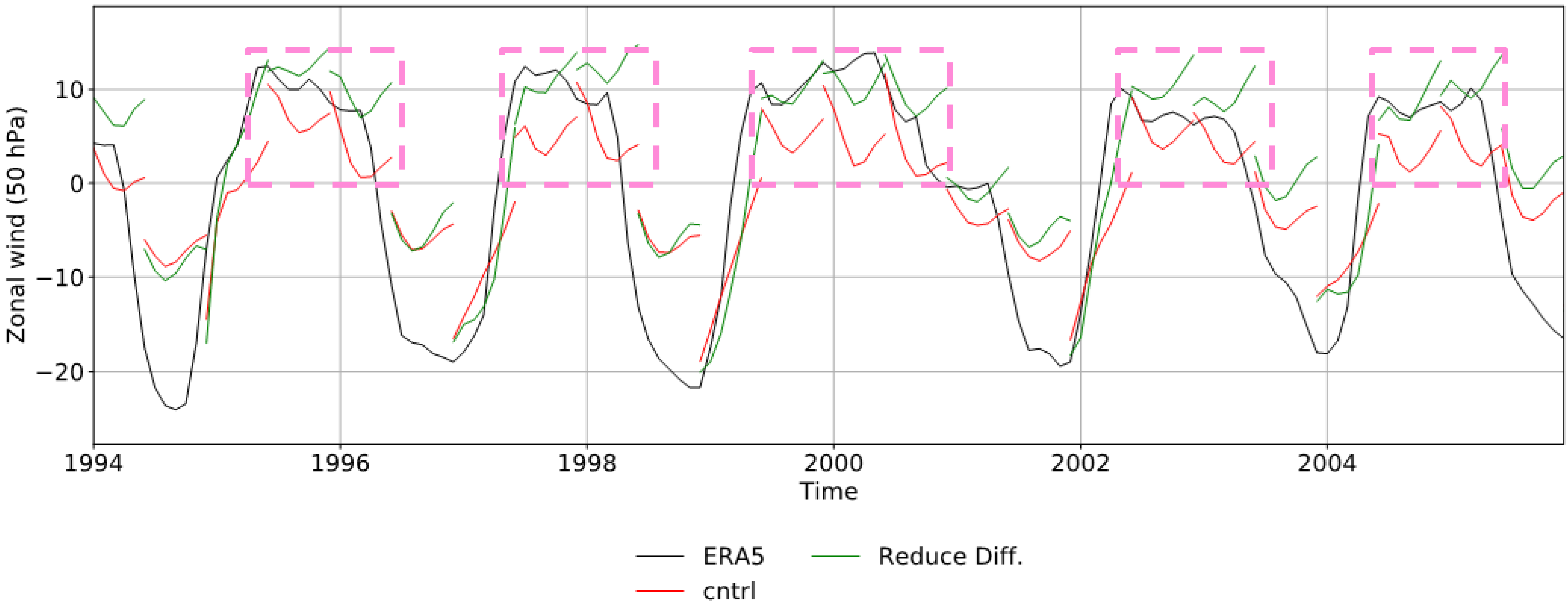
Current model has too weak winds in the QBO positive phase and negative phase



Plot shows 50 hPa zonal winds averaged between 5S – 5N
Seasonal hindcasts run with the ECMWF IFS, 7 months long

Turbulent diffusion in the stratosphere

Reduced diffusion improves model winds in the QBO positive phase

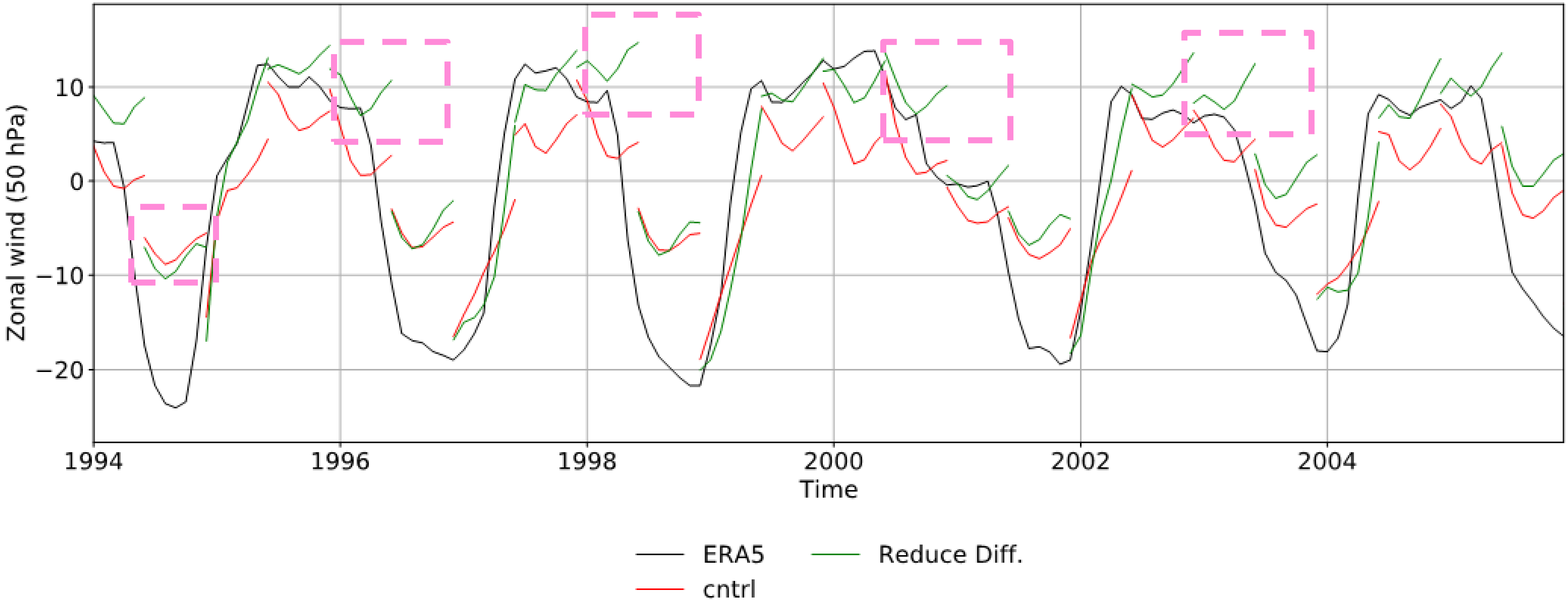


Plot shows 50 hPa zonal winds averaged between 5S – 5N
Seasonal hindcasts run with the ECMWF IFS, 7 months long

ECMWF

Turbulent diffusion in the stratosphere

Reduced diffusion improves model winds in the QBO positive phase but does not make things better at the longer range



Plot shows 50 hPa zonal winds averaged between 5S – 5N
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ECMWF

Turbulent kinetic energy (TKE) closure

'Local' turbulence closure: eddy diffusion above the surface

Momentum

$$\overline{u'w'} \sim -K_M \frac{\partial \overline{u}}{\partial z}$$

Thermodynamics

$$\overline{\theta'w'} \sim -K_H \frac{\partial \overline{\theta}}{\partial z}$$

K_M, K_H and K_q are the exchange coefficients of momentum, heat and moisture

Their magnitude determines the transfer of these conserved quantities from turbulent eddies

‘Local’ turbulence closure: eddy diffusion above the surface

Momentum

$$\overline{u'w'} \sim -K_M \frac{\partial \overline{u}}{\partial z} = -l^2 \left|\frac{\partial \overline{u}}{\partial z}\right| f_M(Ri) \frac{\partial \overline{u}}{\partial z}$$

Thermodynamics

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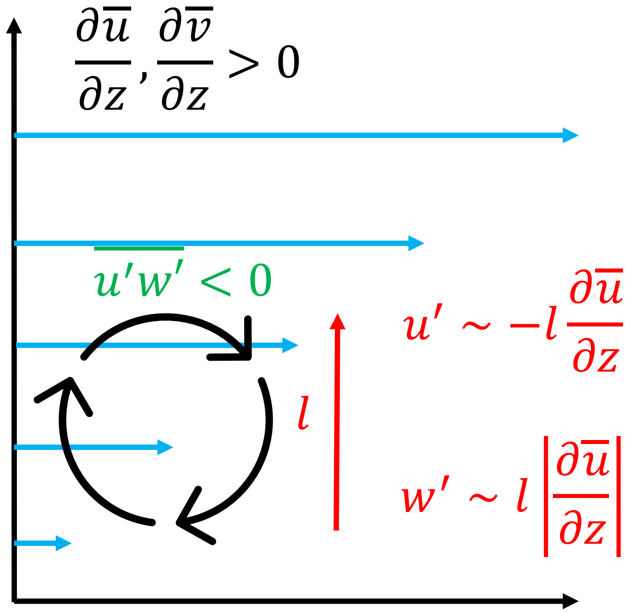
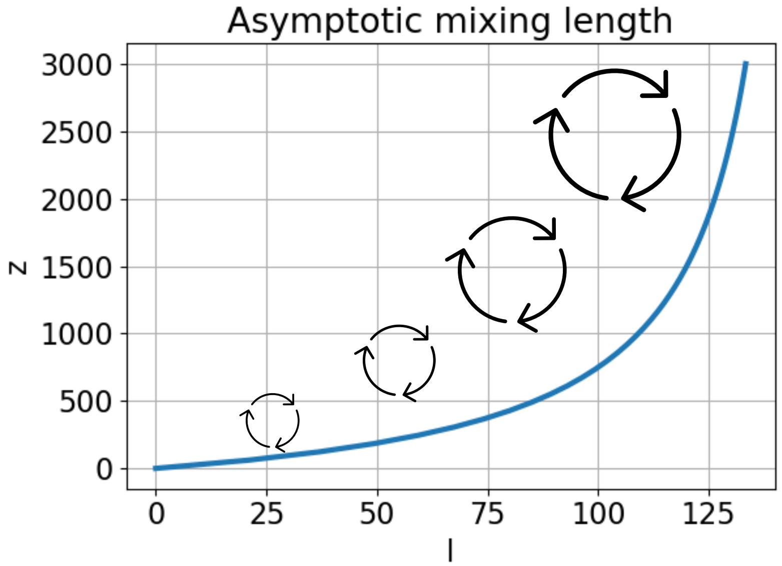


Size of eddies get larger further away from the surface:

$$l \sim \frac{\kappa z \lambda}{\kappa z + \lambda}$$

κ =von-Karman constant

λ =asymptotic mixing length (150 m)



$f_M(Ri)$, $f_H(Ri)$ determined empirically and depend on $Ri(z)$, since we are away from the surface

Turbulent kinetic energy (TKE) closure

Momentum

$$\overline{u'w'} \sim -K_M \frac{\partial \overline{u}}{\partial z} = -C_k \chi_3\left(Ri_f^*\right)\sqrt{e_k}\, L_k \frac{\partial \overline{u}}{\partial z}$$

Thermodynamics

$$\overline{\theta' w'} \sim -K_H \frac{\partial \overline{\theta}}{\partial z} = -C_k C_3 \phi_3\left(Ri_f^*\right)\sqrt{e_k}\, L_k \frac{\partial \overline{\theta}}{\partial z}$$

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TKE $\sqrt{e_k}$ - measure of the turbulence intensity

C_k, C_3 - closure constants

Stability functions $\chi_3(Ri_f^*)$, $\phi_3(Ri_f^*)$- influence of stratification, uses flux Richardson number Ri_f^*

Lengthscale L_k - defines the scale of the turbulence

Turbulent kinetic energy (TKE) closure: it is prognostic

Advantage of the prognostic TKE is that it has ‘memory’, is advected and involves physical source terms :

$$\frac{\partial e_k}{\partial t} = -u \cdot \nabla e_k - \frac{\partial}{\partial z}\left(K_{e_k}\frac{\partial e_k}{\partial z}\right) - ST + BT - \epsilon_k$$

Advection

Turbulent diffusion

Turbulent kinetic energy (TKE) closure: it is prognostic

Advantage of the prognostic TKE is that it has ‘memory’, is advected and involves physical source terms :

$$\frac{\partial e_k}{\partial t} = -u \cdot \nabla e_k - \frac{\partial}{\partial z}\left(K_{e_k}\frac{\partial e_k}{\partial z}\right) - ST + BT - \epsilon_k$$

Advection — Turbulent diffusion

TKE:

$$\sqrt{e_k} = \frac{\overline{u'u'} + \overline{v'v'} + \overline{w'w'}}{2}$$

Shear production:

$$ST = -\overline{u'w'}\frac{\partial u}{\partial z} - \overline{v'w'}\frac{\partial v}{\partial z} \approx \mathrm{K_M}\left|\frac{\partial u}{\partial z}\right|$$

Buoyancy production

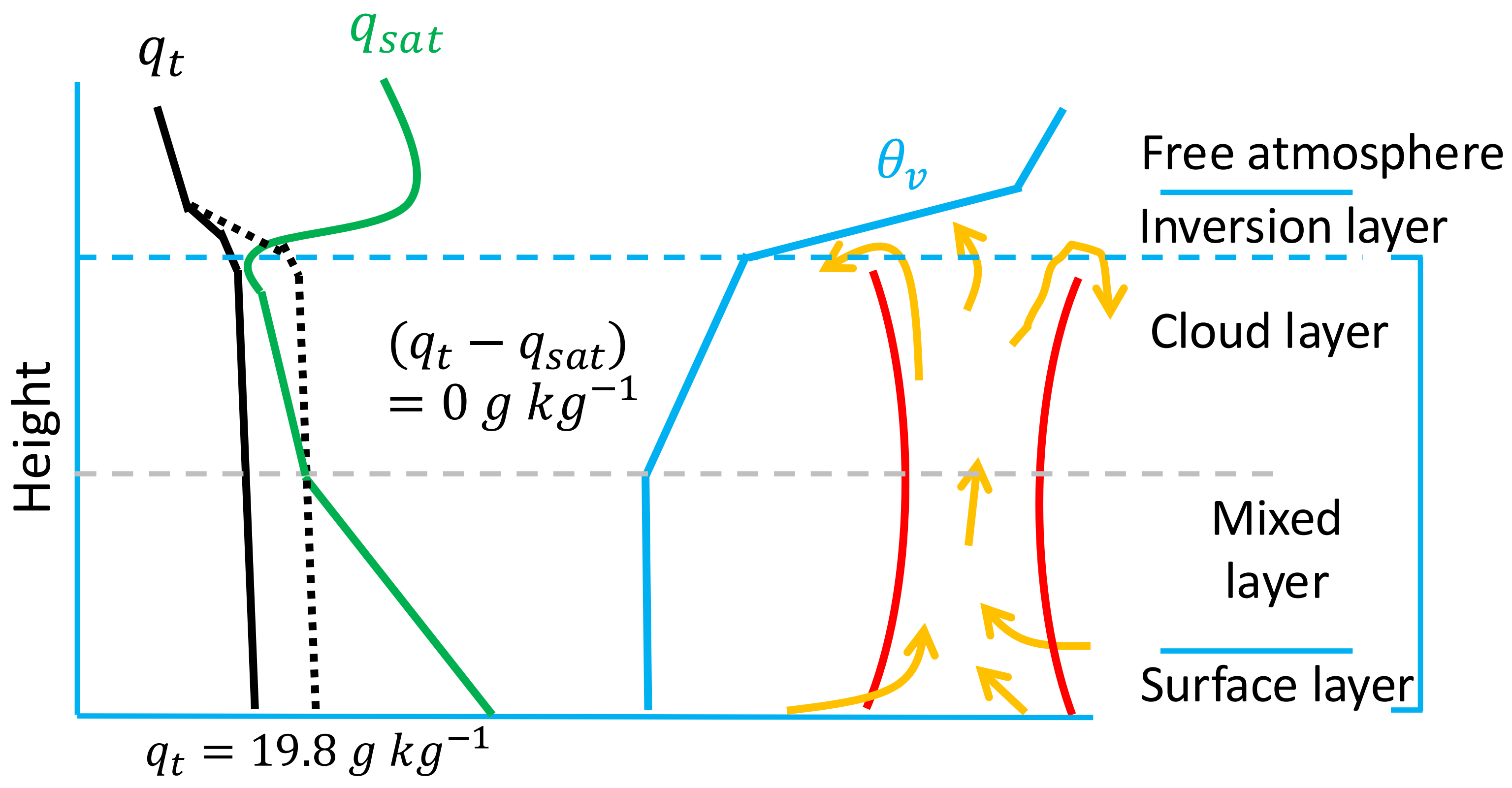
$$BT = \frac{g}{\theta}\overline{\theta'w'} \approx -\mathrm{K_H}\frac{g}{\theta}\frac{\partial\theta}{\partial z}$$

Dissipation:

$$\epsilon_k = \frac{2e_k}{\tau_k} \approx C_\epsilon \frac{e_k^{\frac{2}{3}}}{L_\epsilon}$$

Impact of TKE on low level cloud cover

Stratoculums topped PBLs are very sensitive to mixing



The presence of stratocumulus is sensitive to:

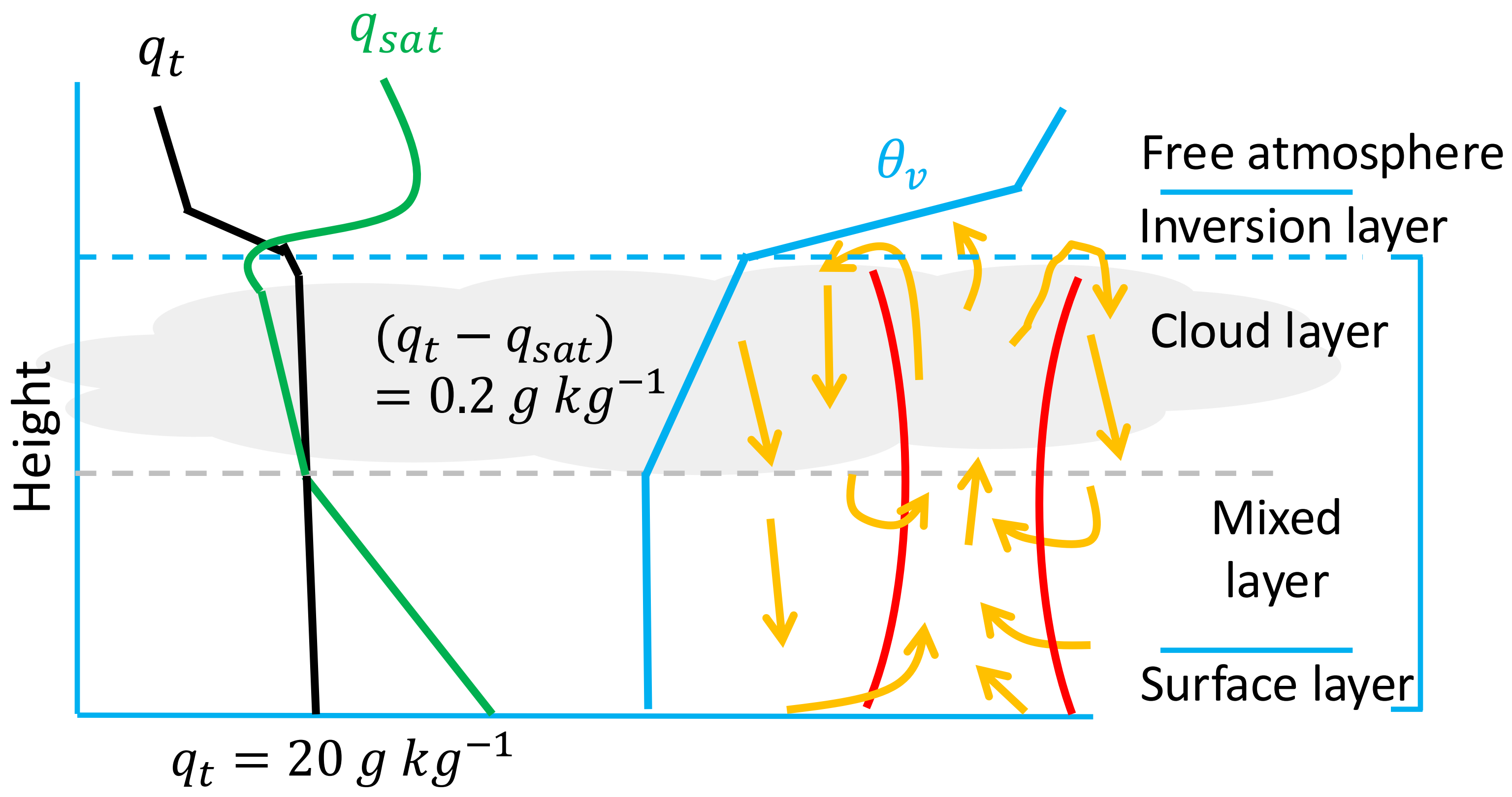
- Small variations in humidity

Mixing in stratocumulus clouds is more complex due to:

- Stronger entrainment from free atmosphere
- Condensation within cloud
- Radiative heating/cooling, which is essential for cloud evolution

ECMWF

Stratoculums topped PBLs are very sensitive to mixing



The presence of stratocumulus is sensitive to:

- Small variations in humidity

- Small variations in temperature

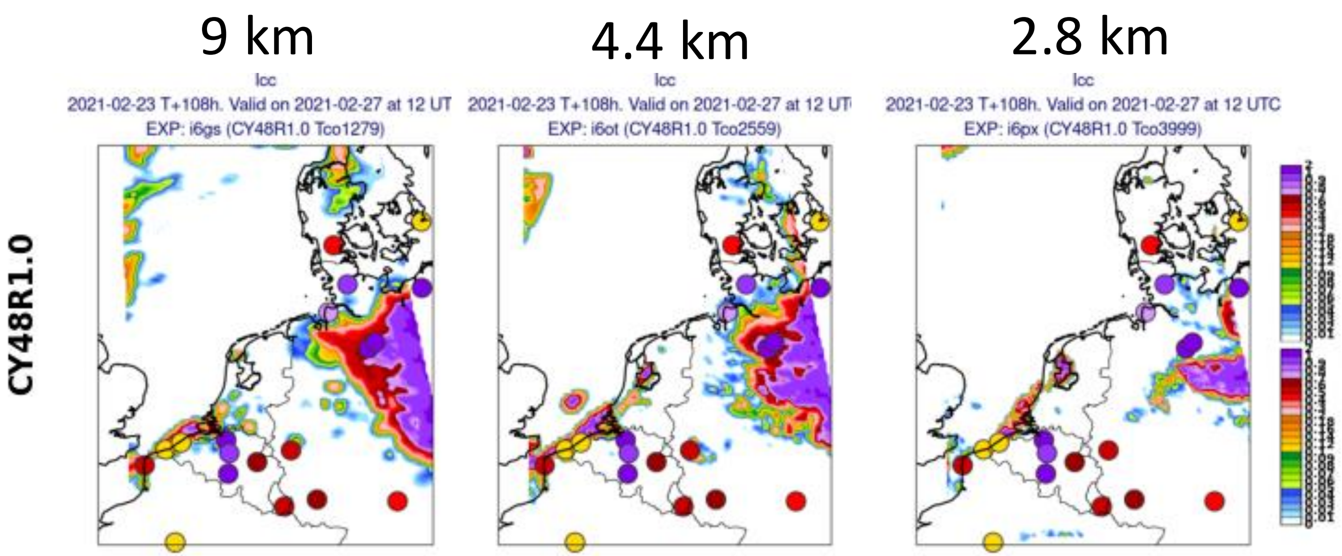
Mixing in stratocumulus clouds is more complex due to:
- Stronger entrainment from free atmosphere
- Condensation within cloud
- Radiative heating/cooling, which is essential for cloud evolution

ECMWF

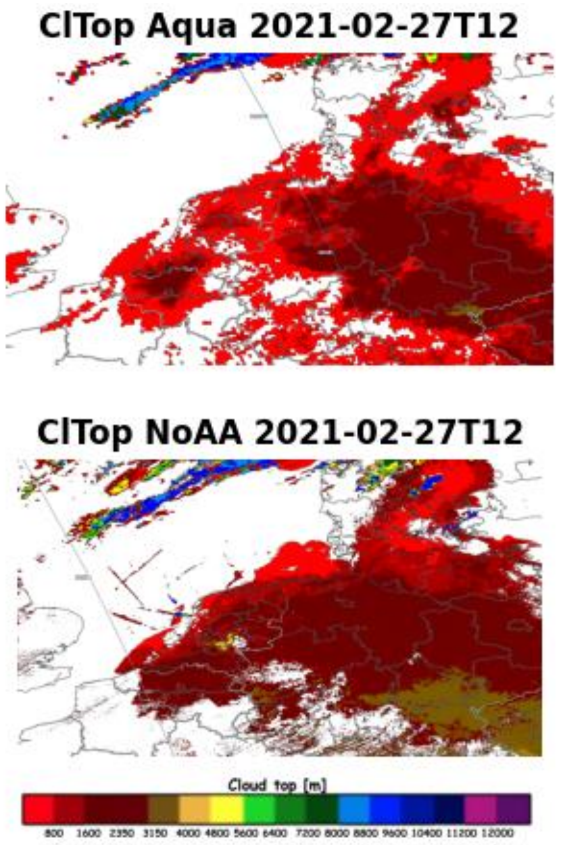
Impact of TKE on low level clouds

Current turbulence scheme underestimates low cloud cover

Horizontal resolution



Observation of cloud top height



Figures c/o Ivan Bastak-Duran

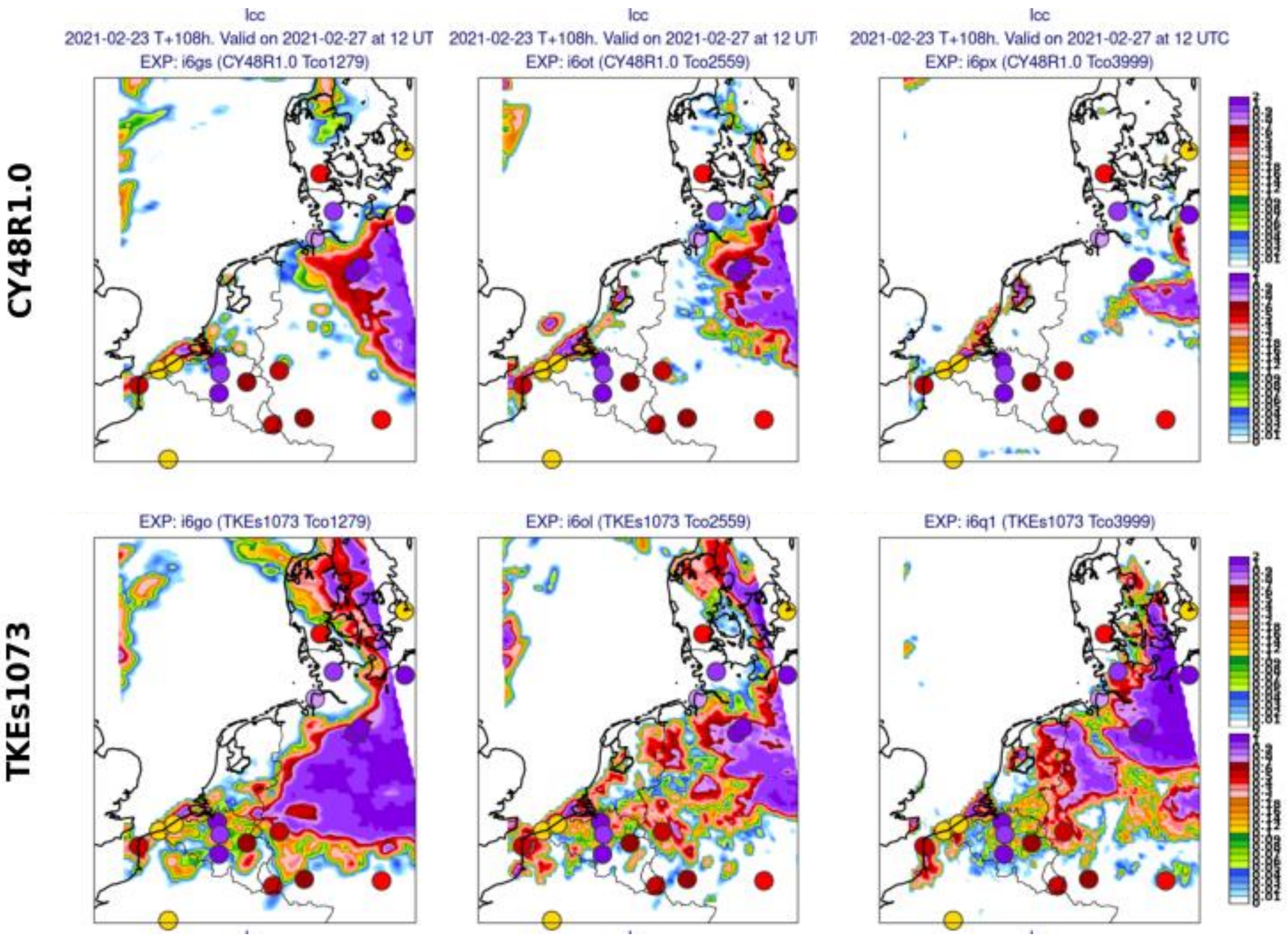
Impact of TKE on low level clouds

Horizontal resolution

9 km | 4.4 km | 2.8 km

Current turbulence scheme underestimates low cloud cover

TKE scheme tends to have less mixing in these cases, and so can maintain low cloud



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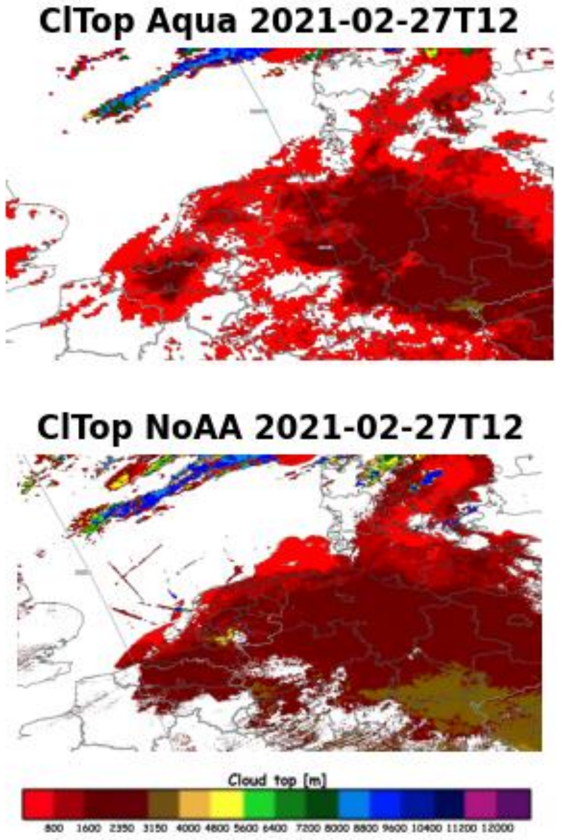


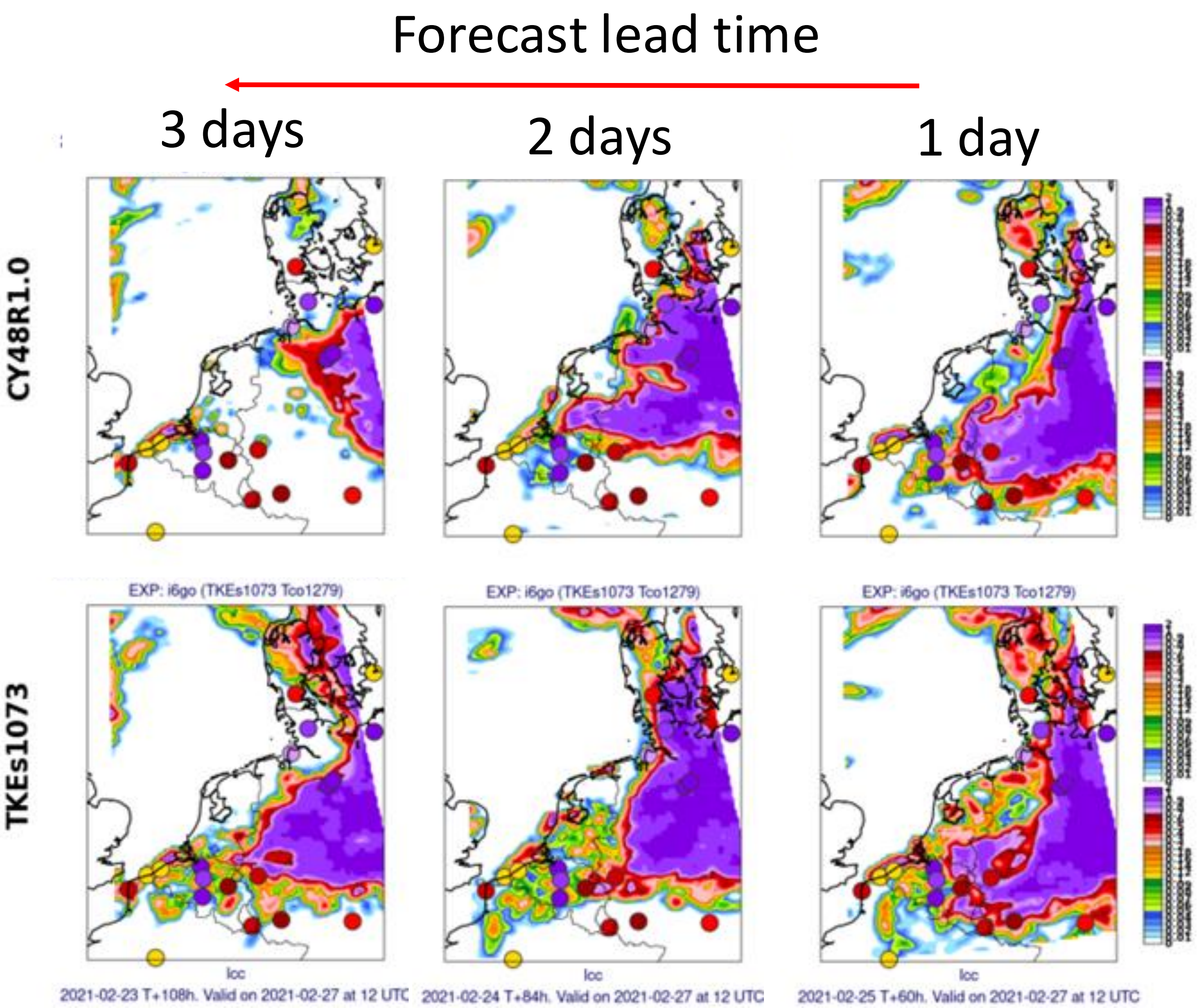
Figures c/o Ivan Bastak-Duran

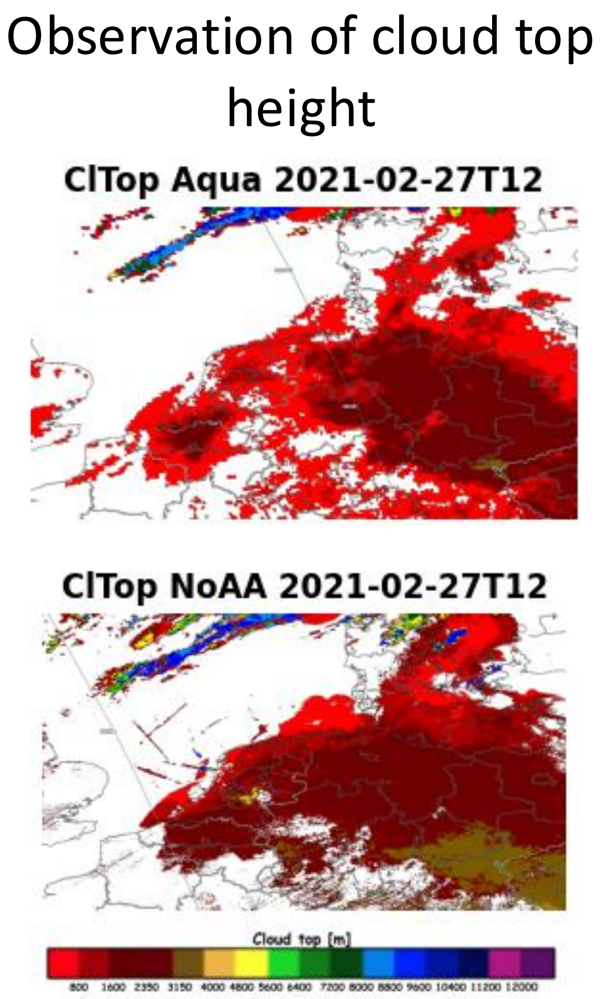
ECMWF

Impact of TKE on low level clouds

Current scheme cannot maintain low cloud – mixed too rapidly

TKE scheme has low cloud even at a lead time of 3 days





Figures c/o Ivan Bastak-Duran

ECMWF

Summary of BL parametrization

- **Outer layer diffusion and mass flux:**
  - Local similarity (derived from surface observations) is used in unstable regimes but does not work for stable
  - Local diffusion does not work for convective boundary layers, which is where mass flux is also added
- **IFS parametrization:**
  - Due to the uncertainty in the stability functions, different forms are used throughout the atmosphere
- **Sensitivity to changing stability functions:**
  - Reverting the stability function to their 'empirical' form degrades the forecast, due to reduced mixing
  - However, less mixing in the stratosphere improves the winds in the tropics
- **TKE:**
  - The TKE scheme benefits from having memory and being advected by the flow
  - TKE improves the representation of low cloud cover