# Planetary Boundary Layer 3

## Parametrization and model errors

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# Contents

- Empirical forms of K-closure terms – history of observations and methods
- Uncertainty in observations and the need for ‘tuning’
- Description of IFS scheme
- Sensitivity of forecasts to uncertainties in BL scheme
- Model issues in stable boundary layers
- Using prognostic TKE

# Empirical surface layer stability functions

# This means we can get profiles of $\overline{u}$ and $\overline{\theta}$ from flux

## Momentum

$$\frac{\kappa z}{\phi_M}\frac{\partial \overline{u}}{\partial z} = u_*$$

Integrate:

$$\overline{u}_z = \frac{u_*}{\kappa}\left[\log\left(\frac{z+z_{0m}}{z_{0m}}\right) - \Psi_\mathrm{M}\left(\frac{z+z_{0m}}{L}\right)\right]$$

## Thermodynamics

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

Integrate:

$$\overline{\theta}_z - \overline{\theta}_s = \frac{\theta_*}{\kappa}\left[\log\left(\frac{z+z_{0m}}{z_{0H}}\right) - \Psi_\mathrm{H}\left(\frac{z+z_{0M}}{L}\right)\right]$$

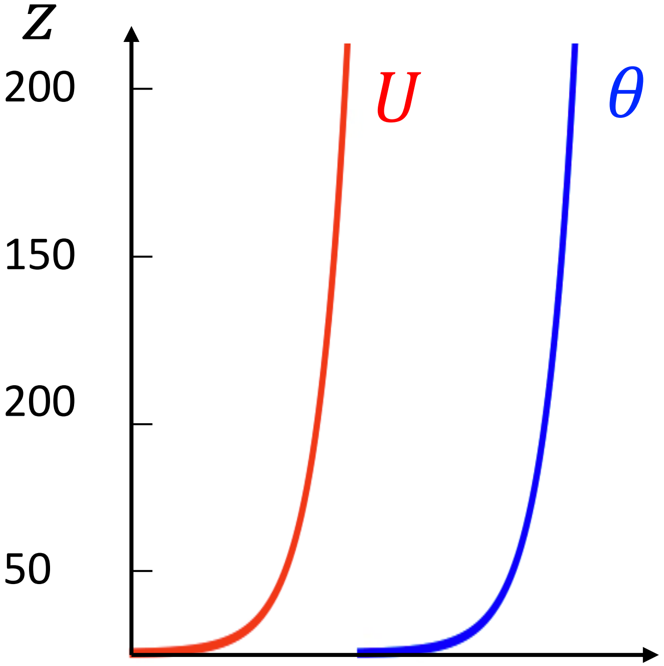
Recall that:

$$\overline{u'w'} = u_*^2$$

$$\overline{\theta' w'} = \theta_* u_*$$

Relationship between $\phi_M(\zeta)$, $\phi_H(\zeta)$ and $\zeta$ measured empirically and then integrated vertically

$\Psi_\mathrm{H}$, $\Psi_\mathrm{M}$ are integrals of $\phi_M(\zeta)$



# This means we can get surface fluxes

## Momentum

$$\rho\overline{u'w'} = \rho u_*^2 = \rho C_M |\overline{u_z}|^2$$

## Thermodynamics

$$\rho\overline{\theta'w'} = \rho u_*\theta_* = \rho C_H(\overline{\theta_z} - \overline{\theta_s})\ |\overline{u_z}|$$

Surface exchange coefficient for heat:

$$\mathrm{C_H} = \frac{\kappa^2}{\left[\log\left(\frac{z+z_{0m}}{z_{0m}}\right) - \Psi_\mathrm{M}\left(\frac{z+z_{0m}}{L}\right)\right]\left[\log\left(\frac{z+z_{0m}}{z_{0H}}\right) - \Psi_\mathrm{H}\left(\frac{z+z_{0m}}{L}\right)\right]}$$

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# Empirical stability functions Cookbook

- Ingredients:
  - Accurate surface layer fluxes ($\overline{u'w'}$, $\overline{\theta'w'}$)
  - Wind and temperature profiles at several heights
  - Wide range of sampled stability

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## Businger et al (1970)

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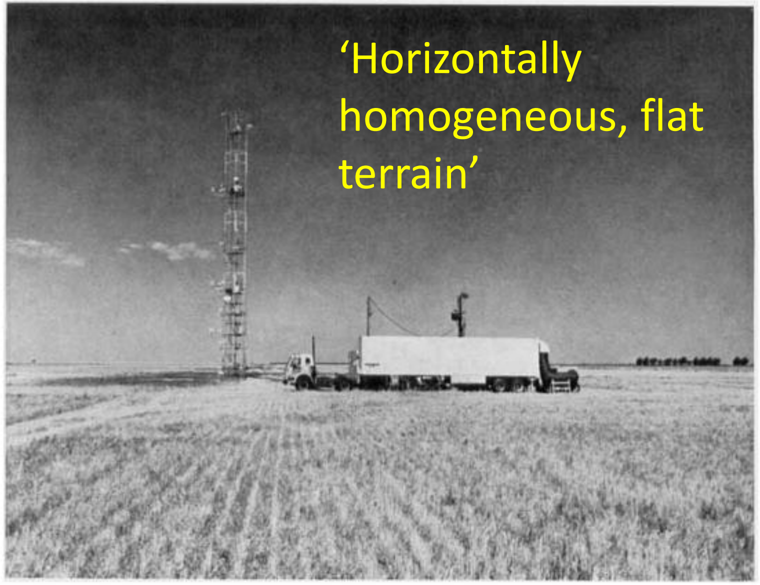
Haugen et al 1971



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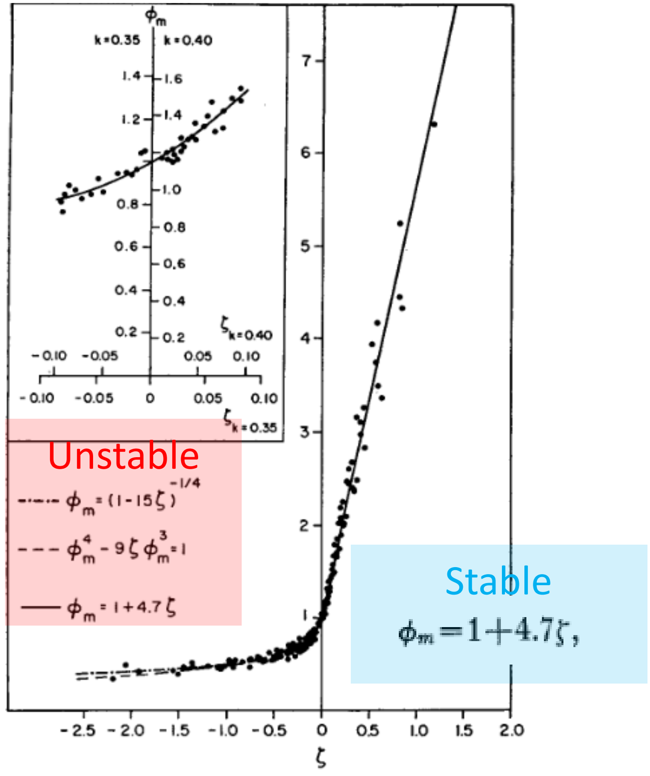
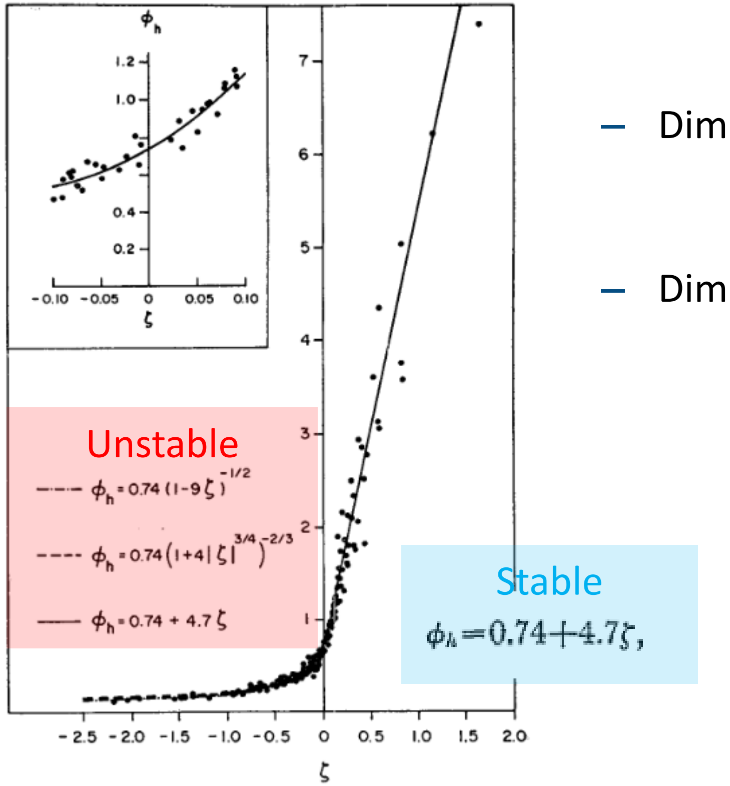
Momentum: $\phi_M$



Heat: $\phi_H$



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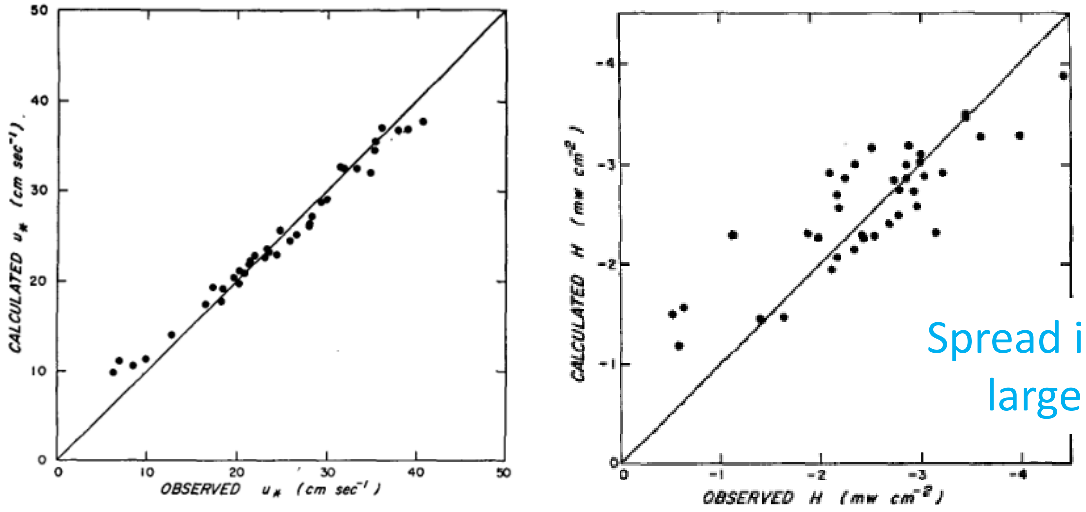
Momentum flux

Heat flux

Spread in the heat fluxes are large in stable regimes

Plots show observed vs calculated heat and momentum fluxes in stable situations

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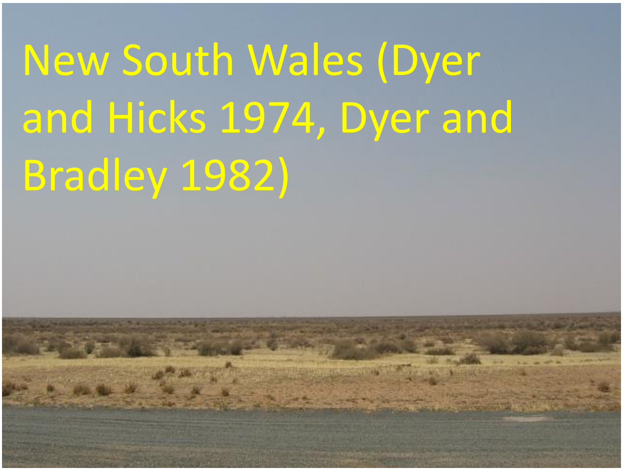

New South Wales (Dyer and Hicks 1974, Dyer and Bradley 1982)

New South Wales, ITCE experiment

Also ‘Horizontally homogeneous, flat terrain’,
…and mostly unstable conditions

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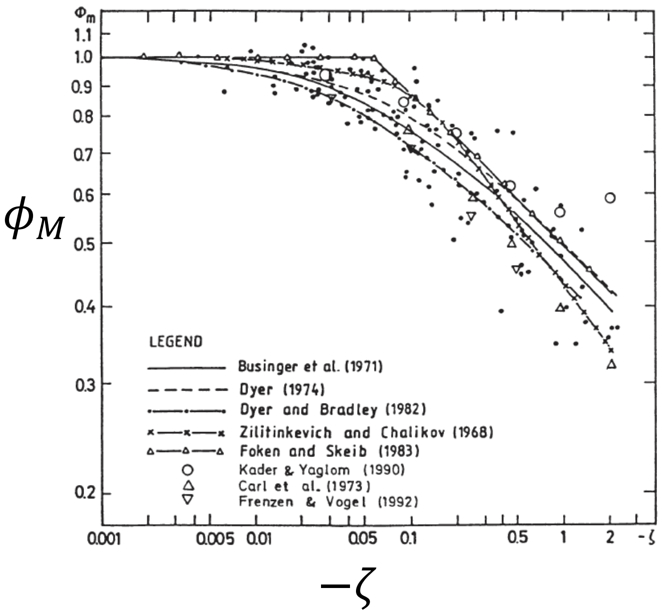
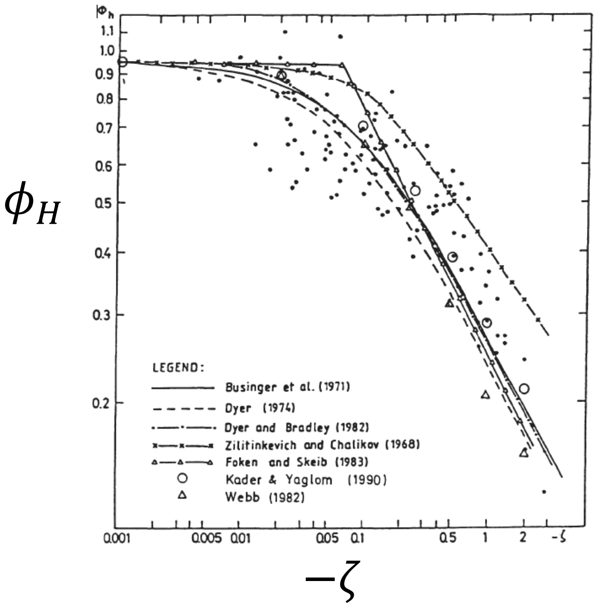
Unstable cases





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There is some disagreement in the functions, depending on where the measurements were taken

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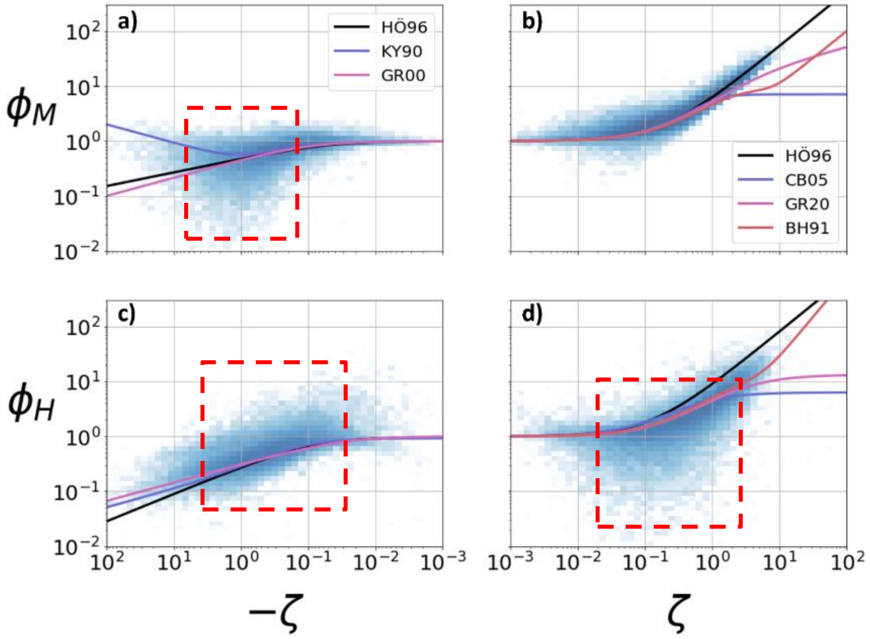
Unstable cases

Stable cases



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There is a large spread in the observed values – making it difficult to fit

Mosso et al, 2023

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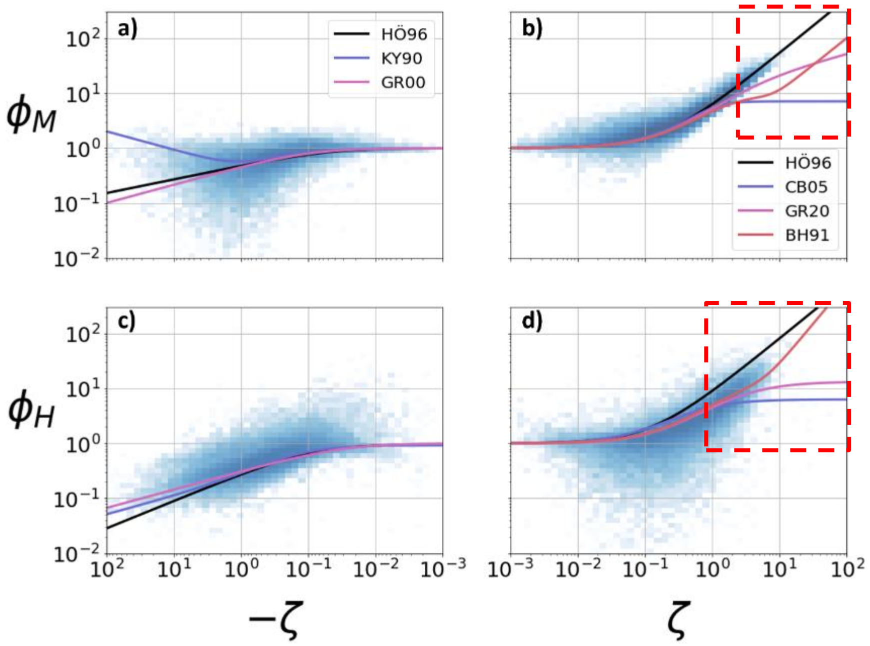
Unstable cases

Stable cases



There is large divergence in the commonly used functions in stable cases – fluxes are small and difficult to measure

Mosso et al, 2023

# Empirical stability functions Cookbook –
## SHEBA site

- Ingredients:
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  - Wind and temperature profiles at several heights
  - Wide range of sampled stability

- Mix well to form:
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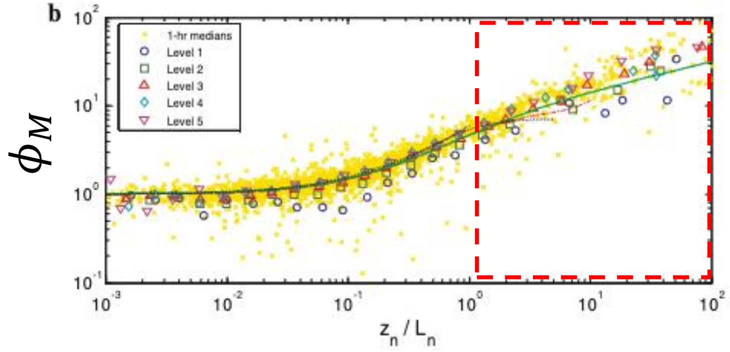
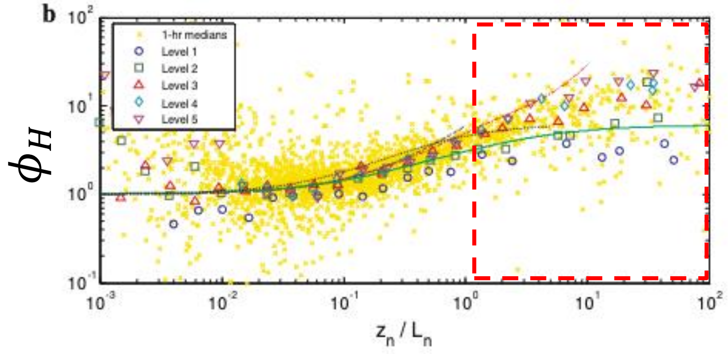
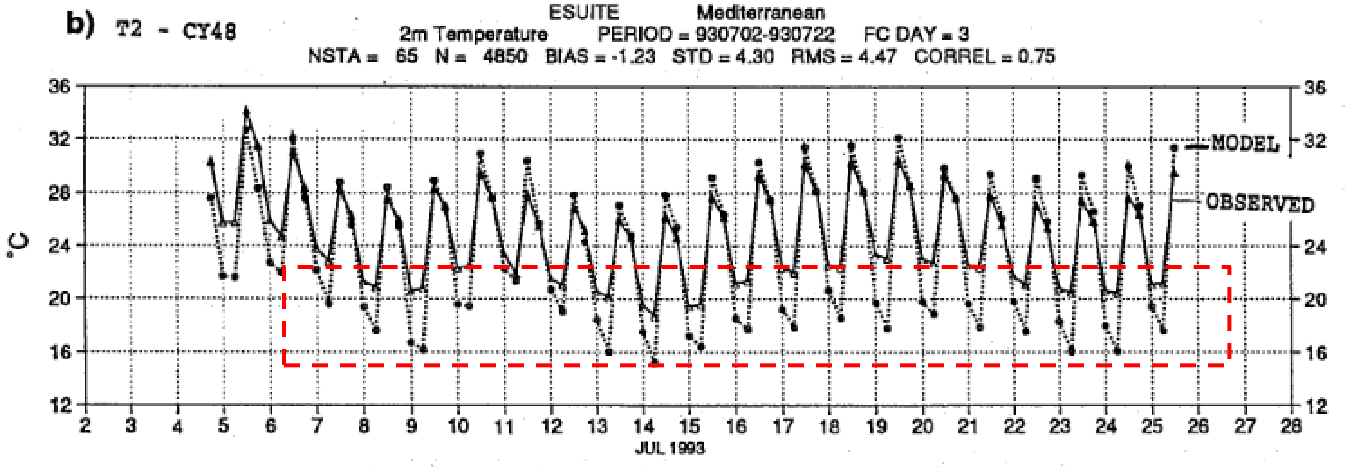
Note that $\frac{z}{L}$ stopped at 2 in Businger et al (1970)





# Observations can only take us so far….

Nighttime (stable regime) temperatures were too cold



Beljaars, 1991

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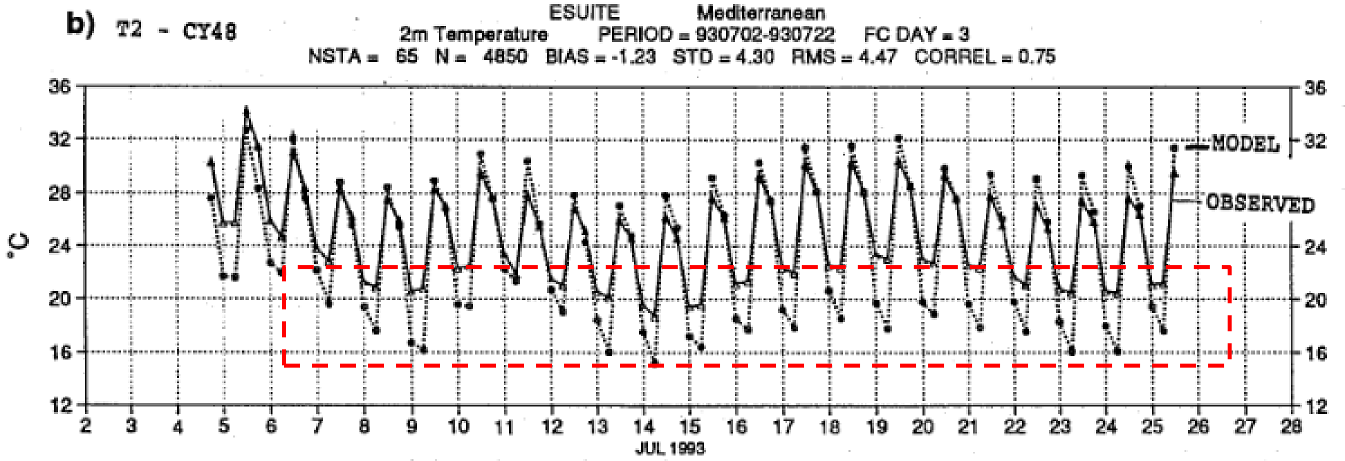
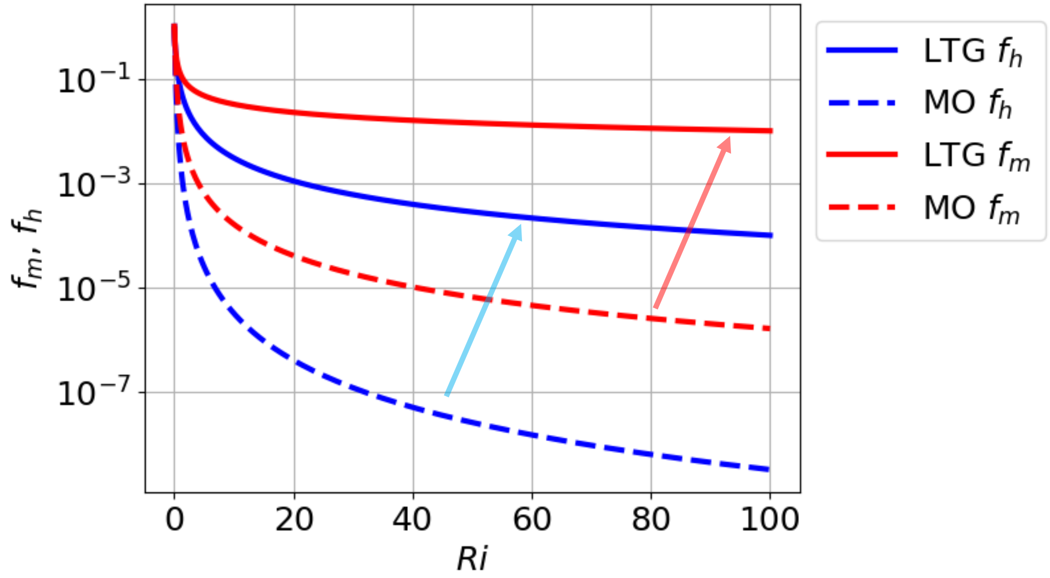


Beljaars, 1991

Mixing was increased in stable BLs



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

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

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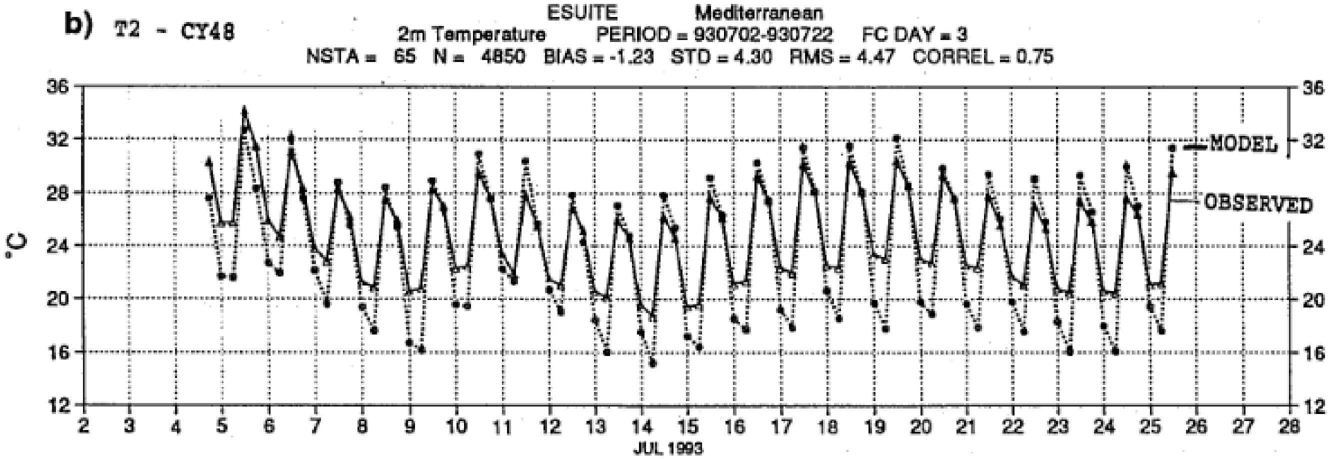

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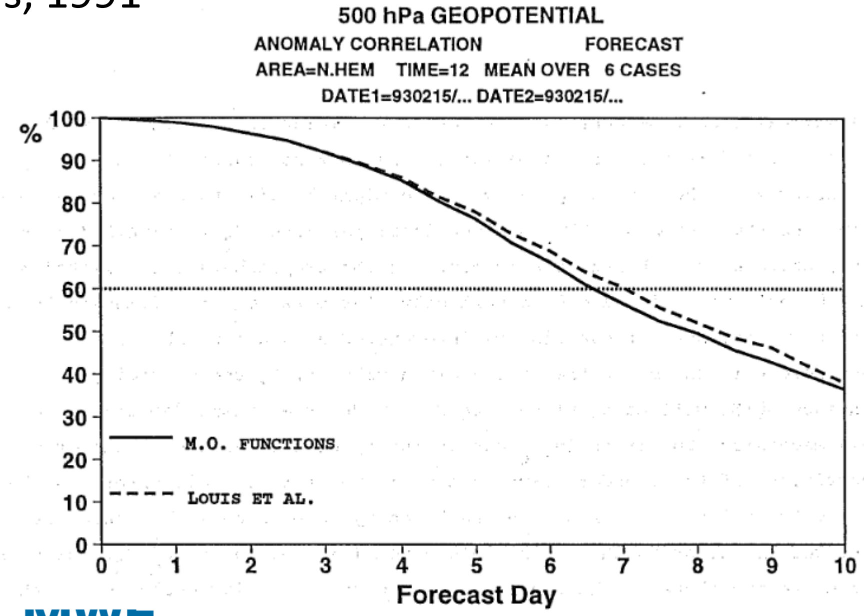

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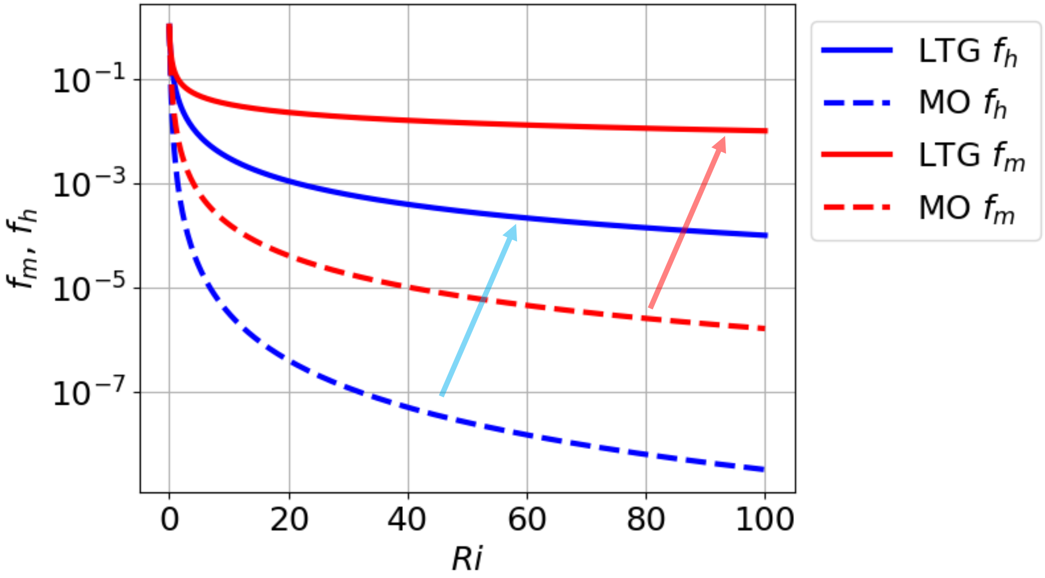

This was a change predominantly motivated by forecast scores, and not direct measurements

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

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

# Summary of empirical stability functions

- Accurate, high frequency and high vertical resolution measurements are required
- Functions used to relate the fluxes and gradients are highly empirical
- Resulting ‘universal’ functions vary from region to region and have large spread
- This could be due to:
    - Heterogeneity of the surface
    - Other processes acting on the profiles (e.g. radiation)
    - Large observational uncertainty in stable conditions when fluxes are small
    - Monin-Obukhov theory not suitable
    - ……

# Description of the current ECMWF IFS scheme

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Stable surface layer

Unstable surface layer

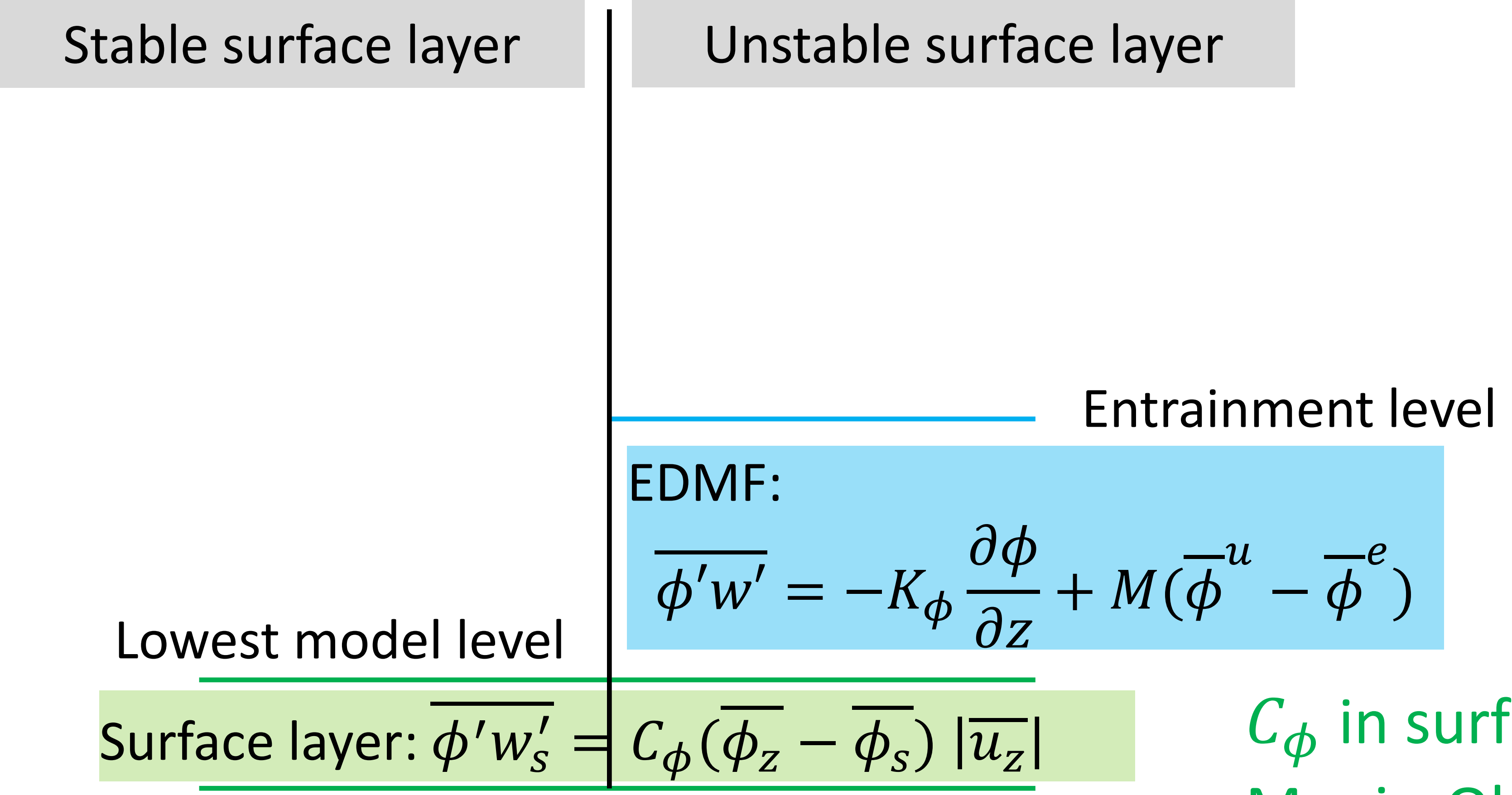
Lowest model level

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

$C_{\phi}$ in surface layer:

Monin-Obukhov, $0 < Ri < 0$

# Description of the current IFS scheme



Stable surface layer

Unstable surface layer

Entrainment level

EDMF:

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

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# Local similarity theory in the outer layer

## Momentum

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

## Thermodynamics

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

- In stable conditions, the mid and upper boundary layer may not be in equilibrium with the surface fluxes
- Local fluxes and stability ($Ri$) dominate
- Local similarity states that the surface layer functions can be used in the outer layer:

$$K_H = \frac{l^2}{\phi_H(\zeta)\phi_M(\zeta)} \left|\frac{\partial \bar{u}}{\partial z}\right|$$

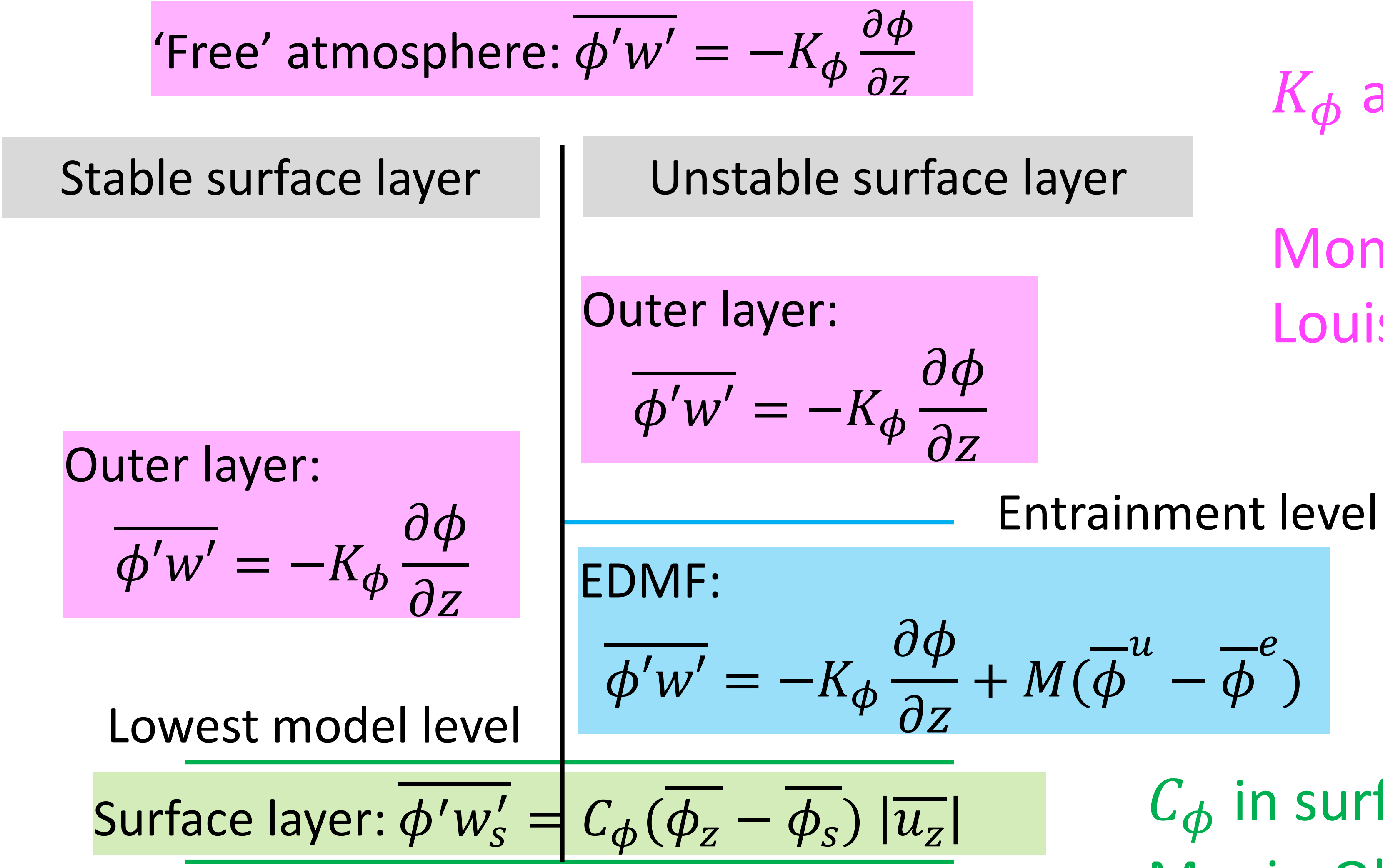
$$K_M = \frac{l^2}{\phi_M^2(\zeta)} \left|\frac{\partial \bar{u}}{\partial z}\right|$$

Use the relation

$$Ri = \zeta \frac{\phi_H(\zeta)}{\phi_M^2(\zeta)}$$

to convert $\zeta$ to the gradient Richardson number in the outer layer

# Description of the current IFS scheme



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

Stable surface layer

Unstable surface layer

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$K_\phi$ above surface:

Monin-Obukhov, $Ri < 0$

Louis, $Ri > 0$

$C_\phi$ in surface layer:

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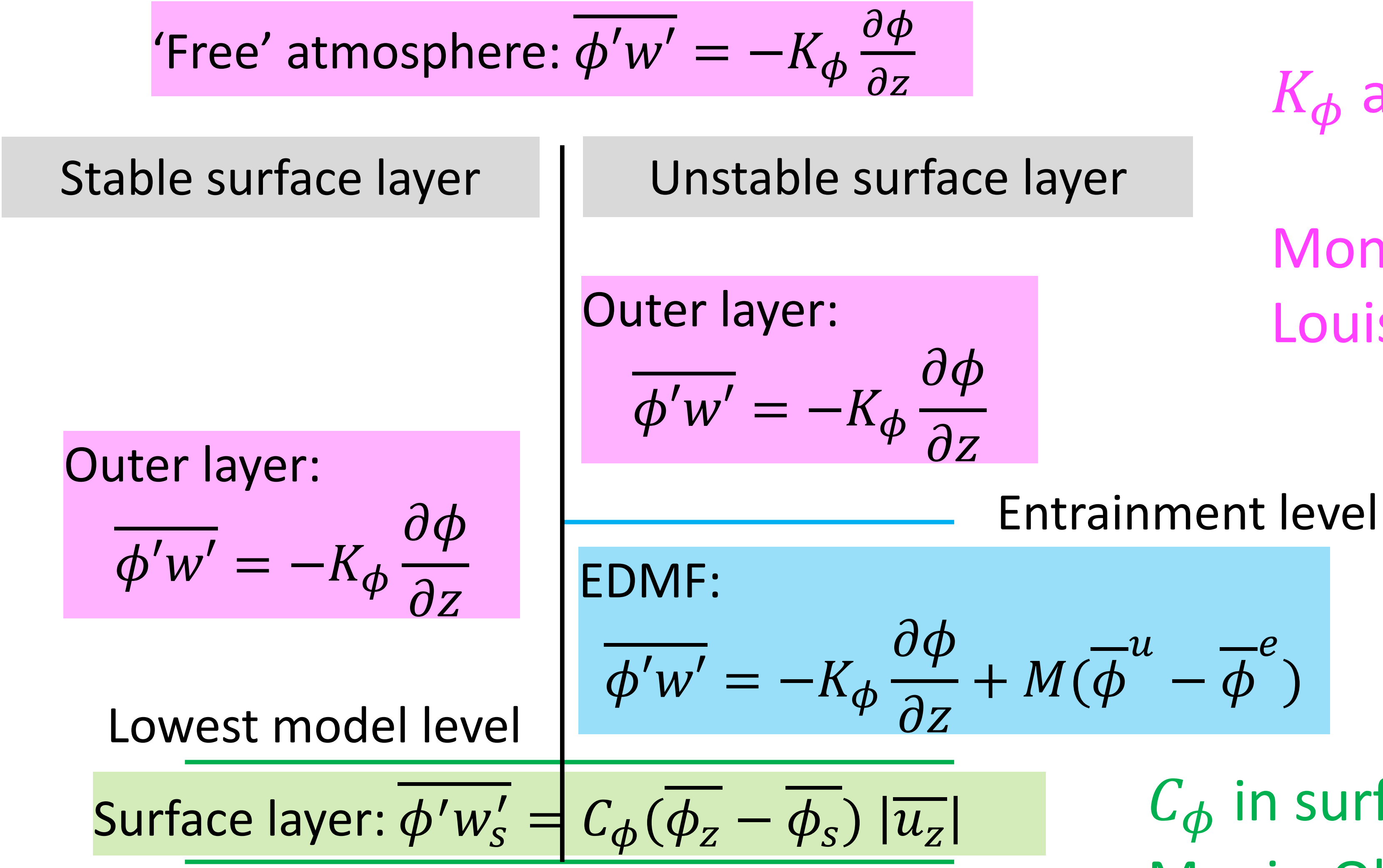
# Impact of changing empirical functions

# Impact of changing functions



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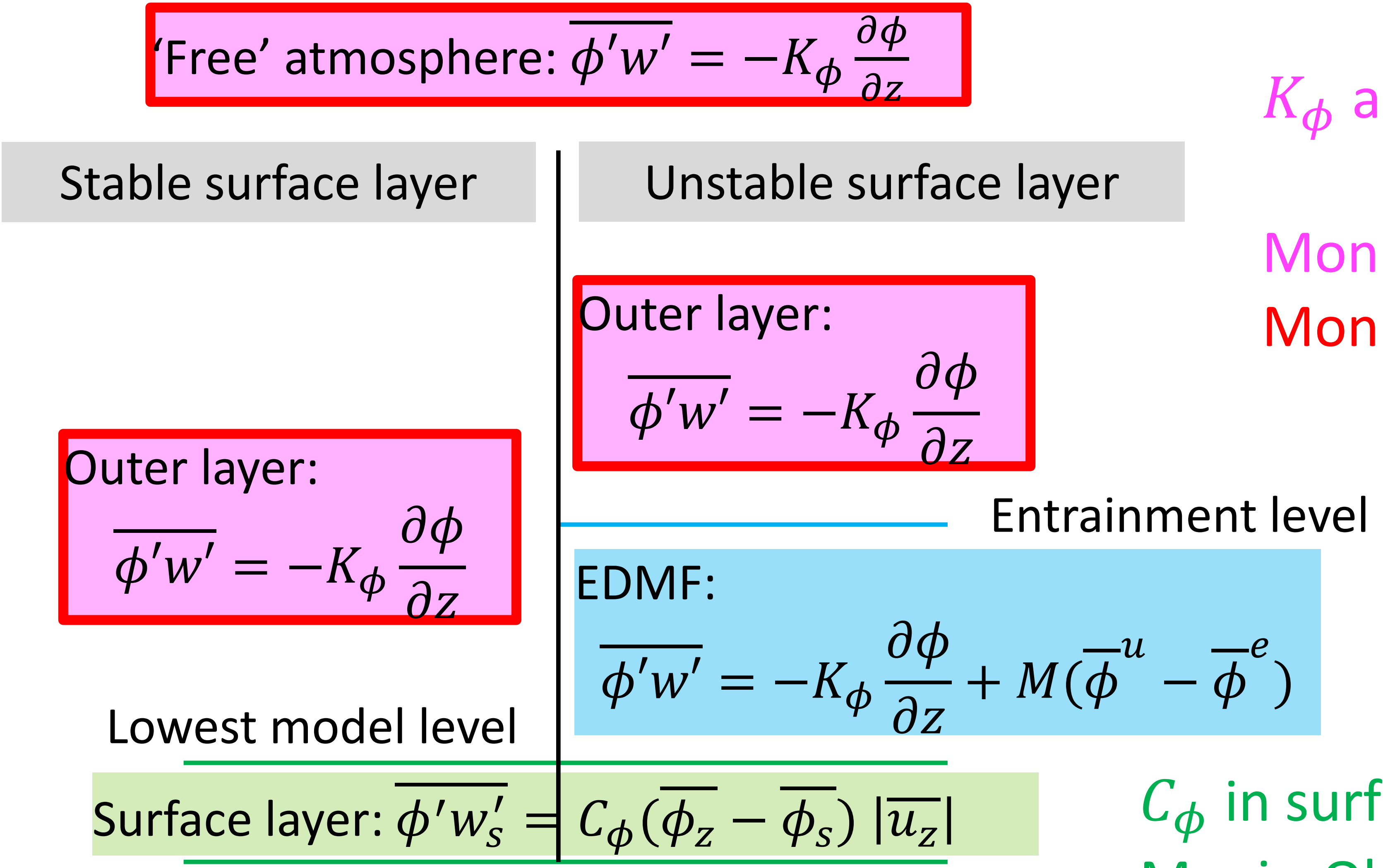
# Impact of changing functions (outer layer)



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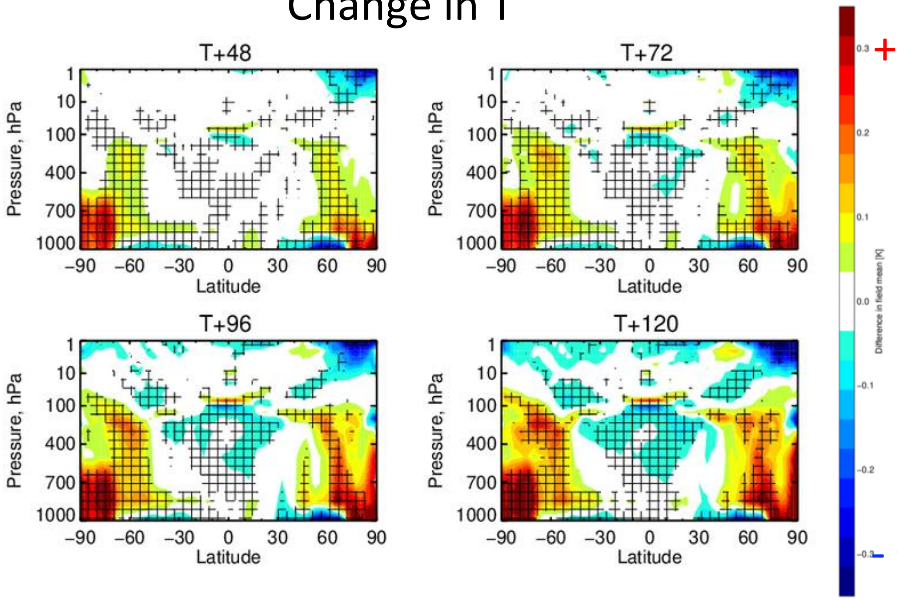
# Changing these back has a large impact on the forecast...

Cooling near the surface and heating above – less mixing

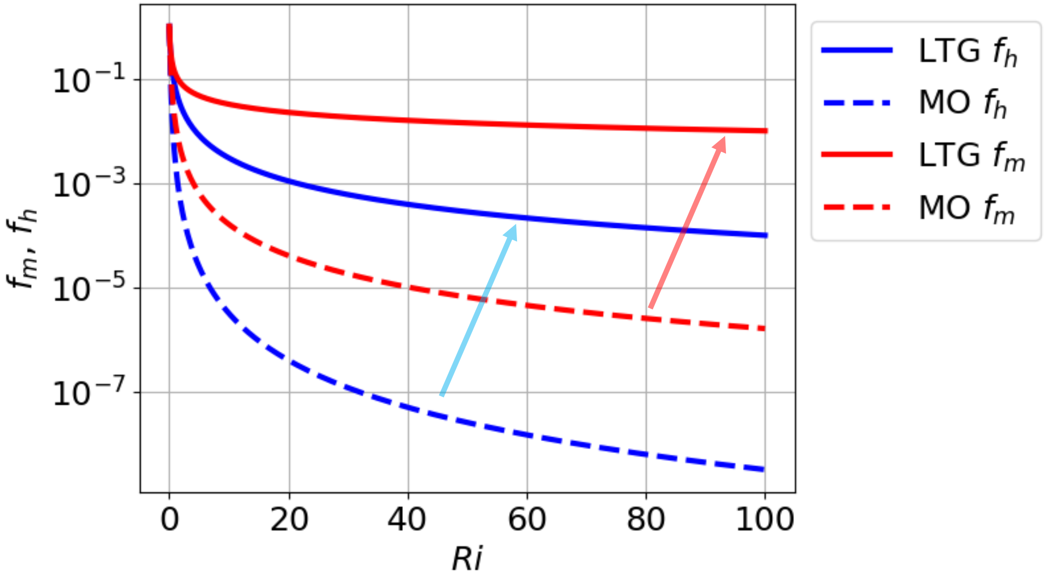
Change in T



+ 0.3 K

- 0.3 K

Mixing was increased in stable BLs



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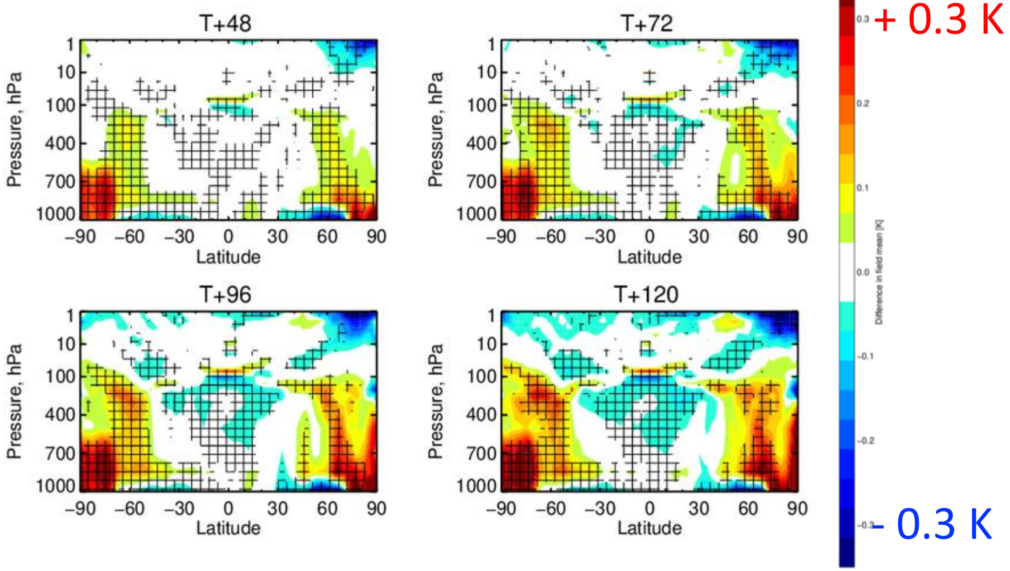
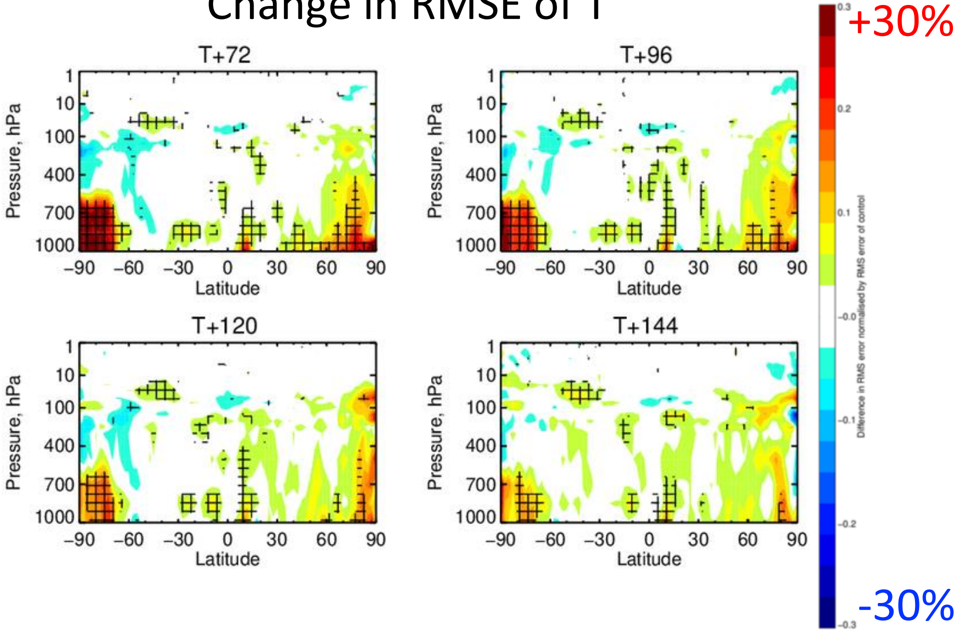


Large degradation of temperature forecast

Change in RMSE of T



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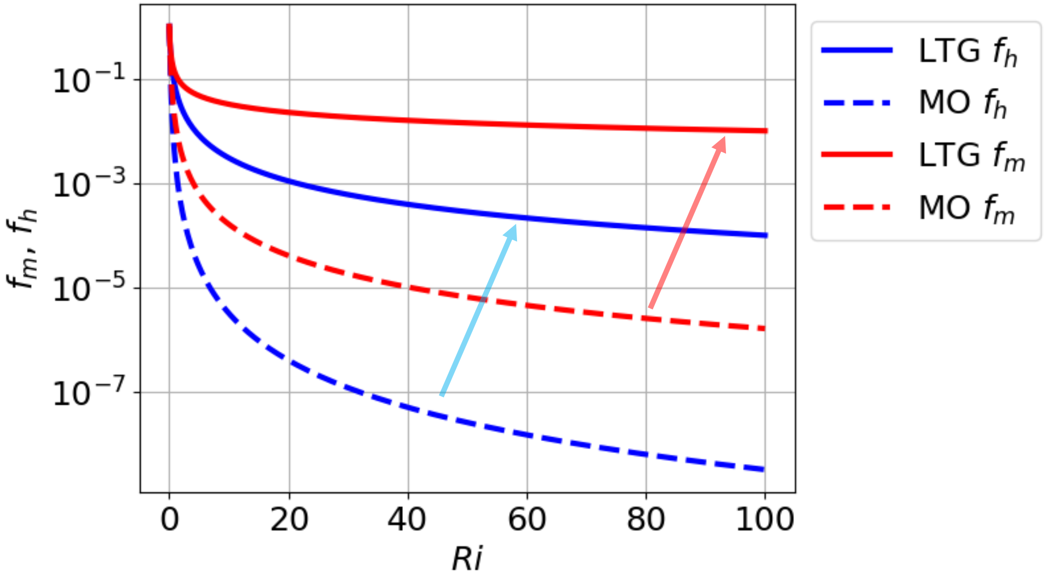

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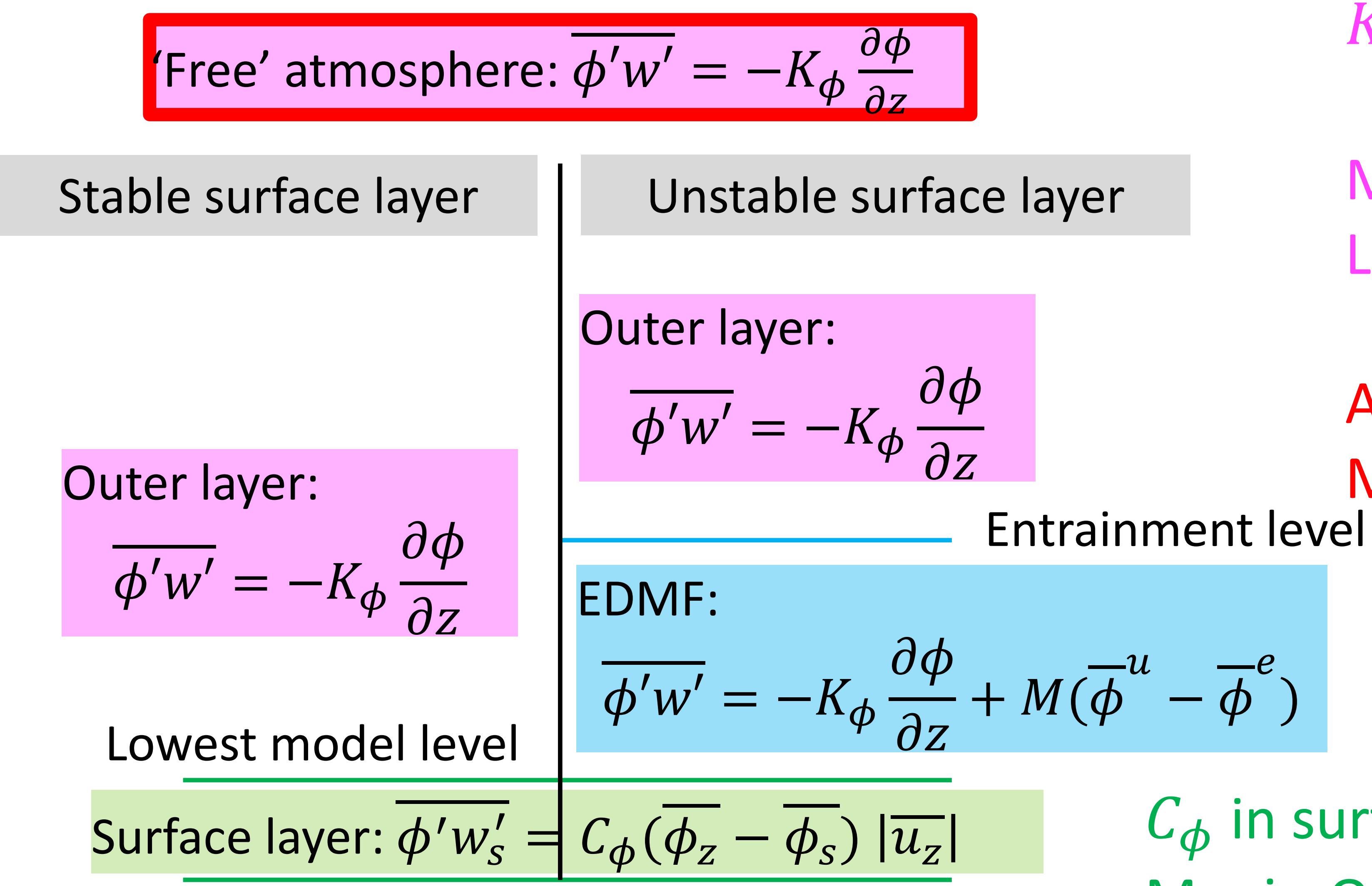
# Impact of changing functions (stratosphere)



'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:

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

Entrainment level

EDMF:

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

Lowest model level

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

$K_\phi$ above surface:

Monin-Obukhov, $Ri < 0$

Louis, $Ri > 0$

Above tropopause:

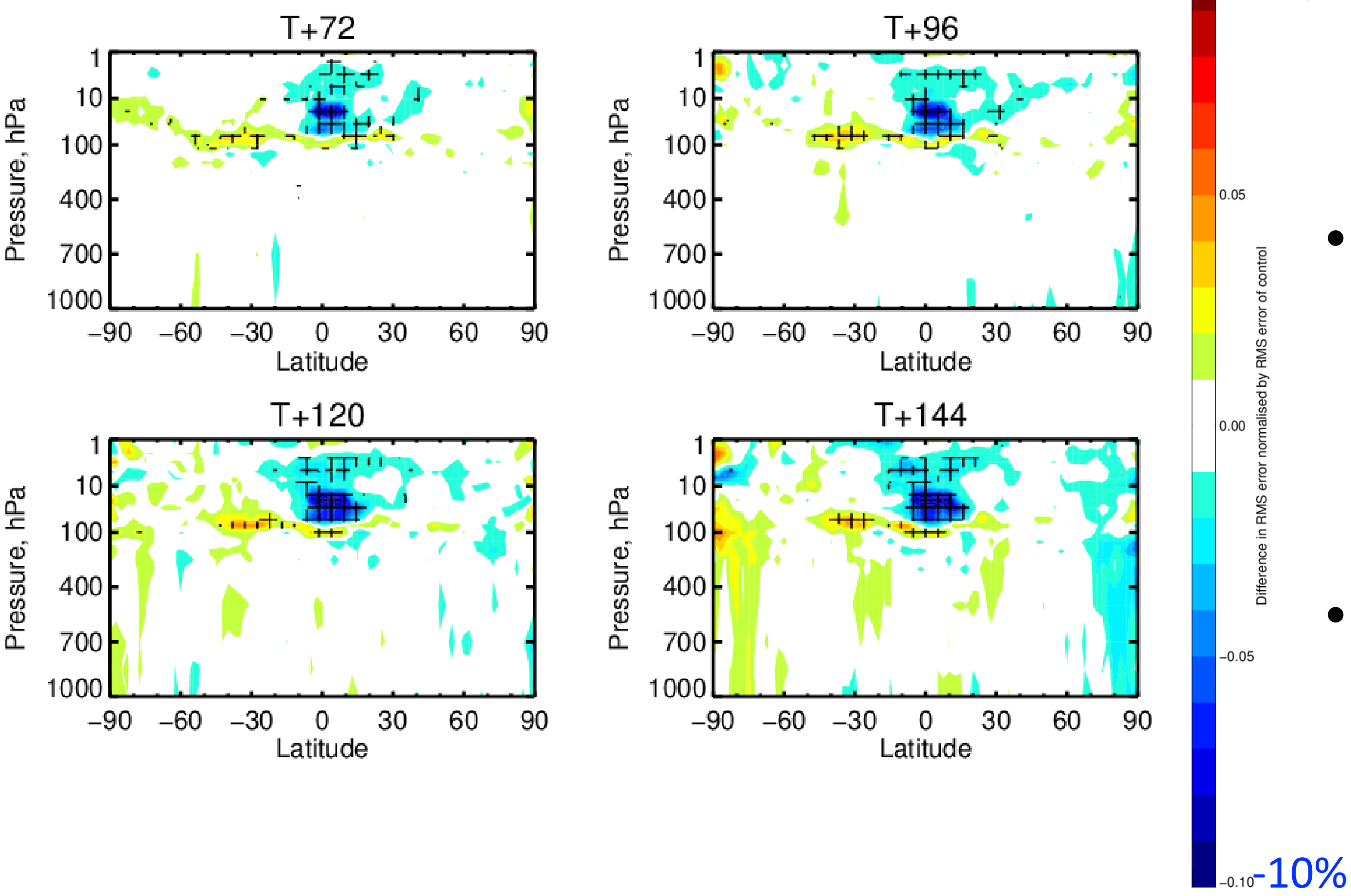
Monin-Obukhov, $Ri > 0$

$C_\phi$ in surface layer:

Monin-Obukhov, $0 < Ri < 0$

# 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

# Impact of changing functions (stratosphere)

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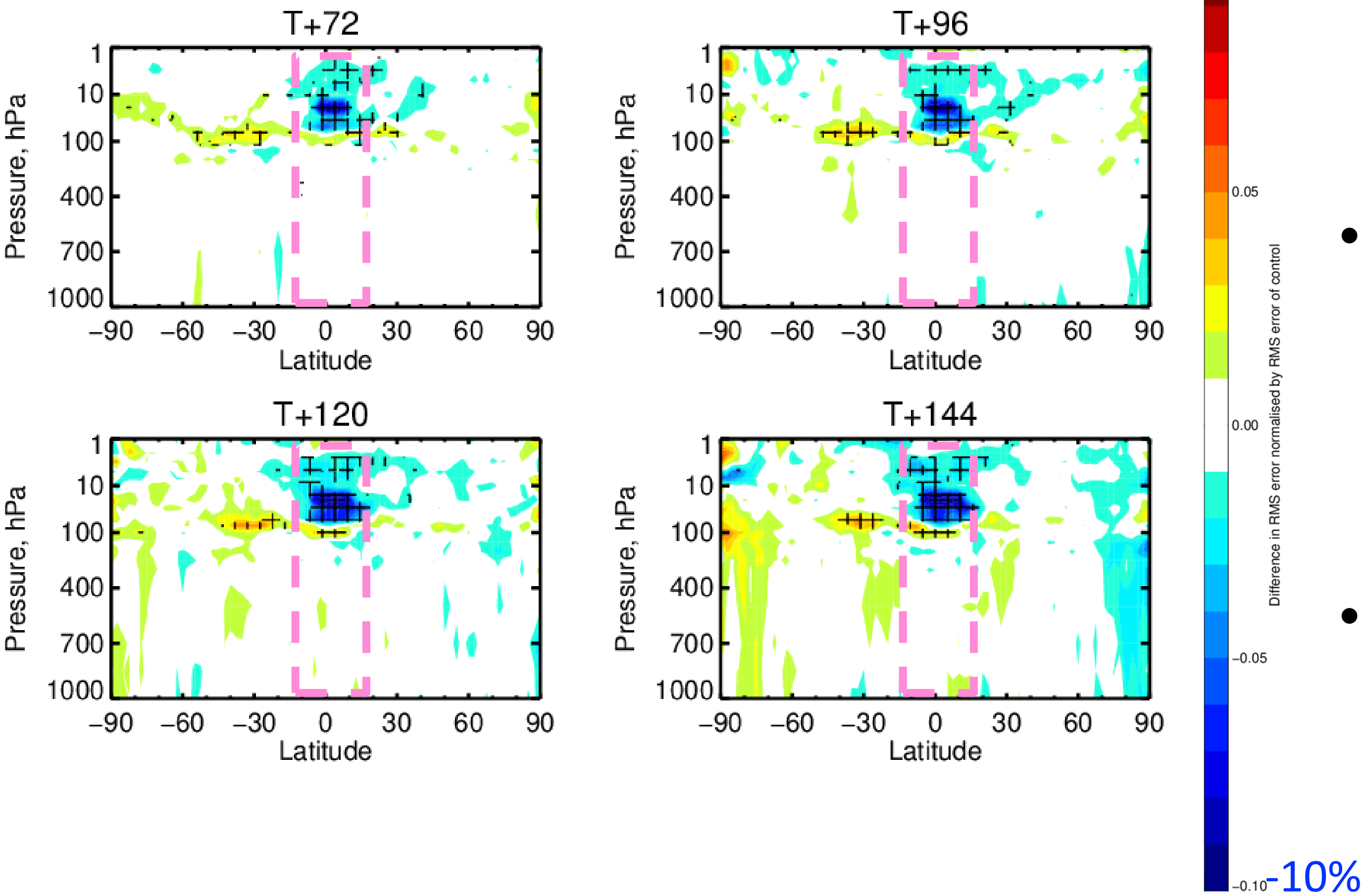

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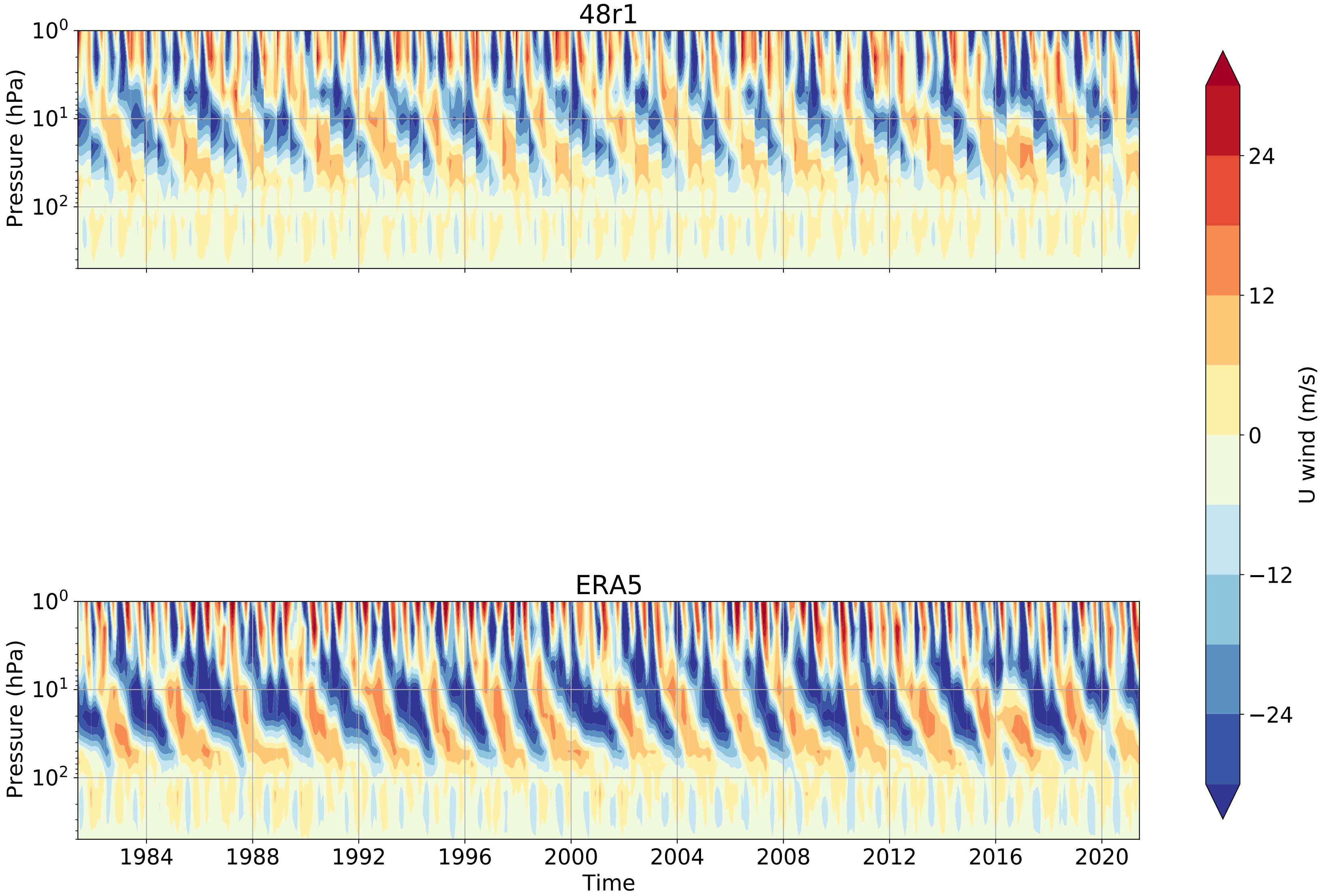
# Turbulent diffusion in the stratosphere

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


Zonal winds averaged between 5S – 5N

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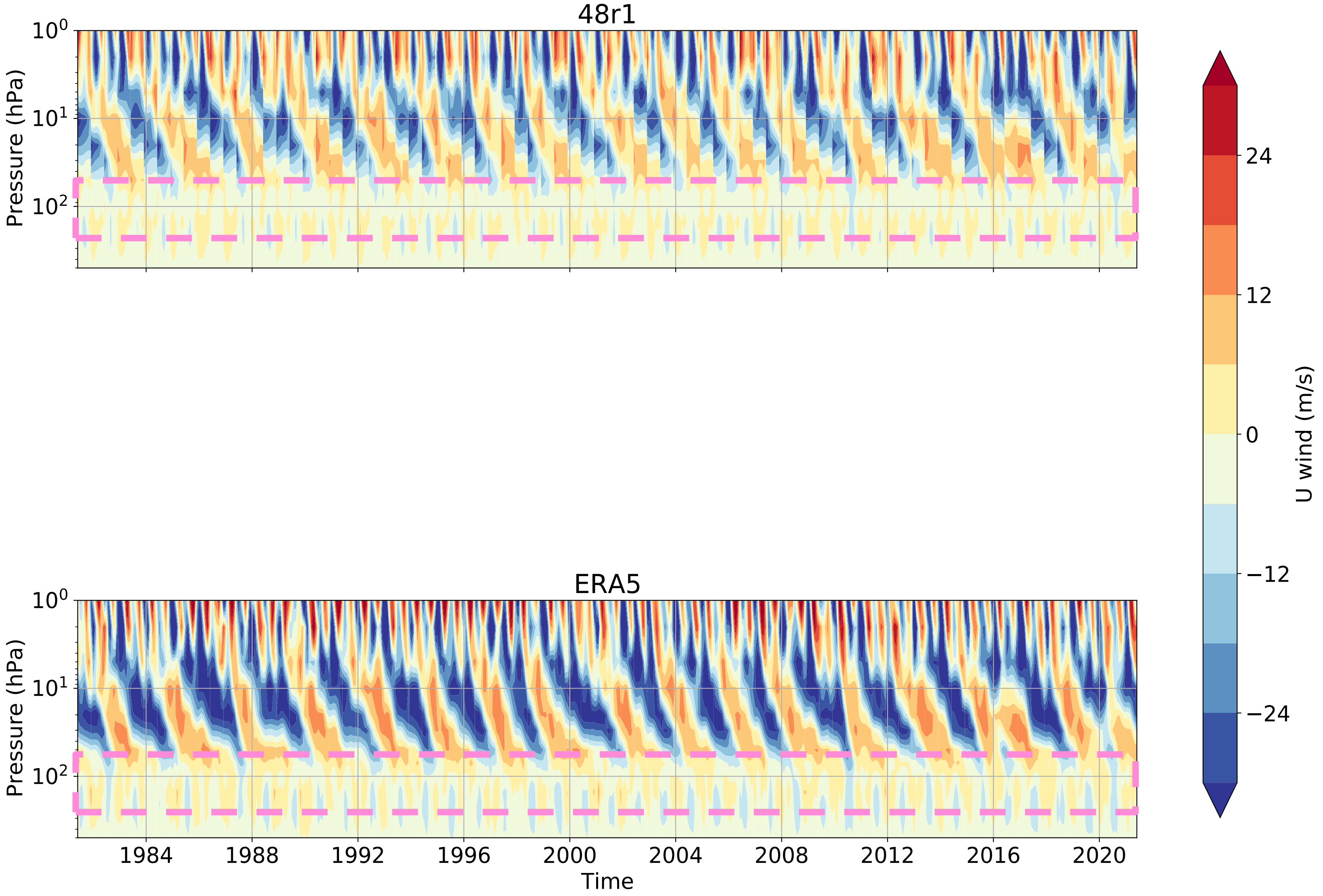

ECMWF

# Turbulent diffusion in the stratosphere

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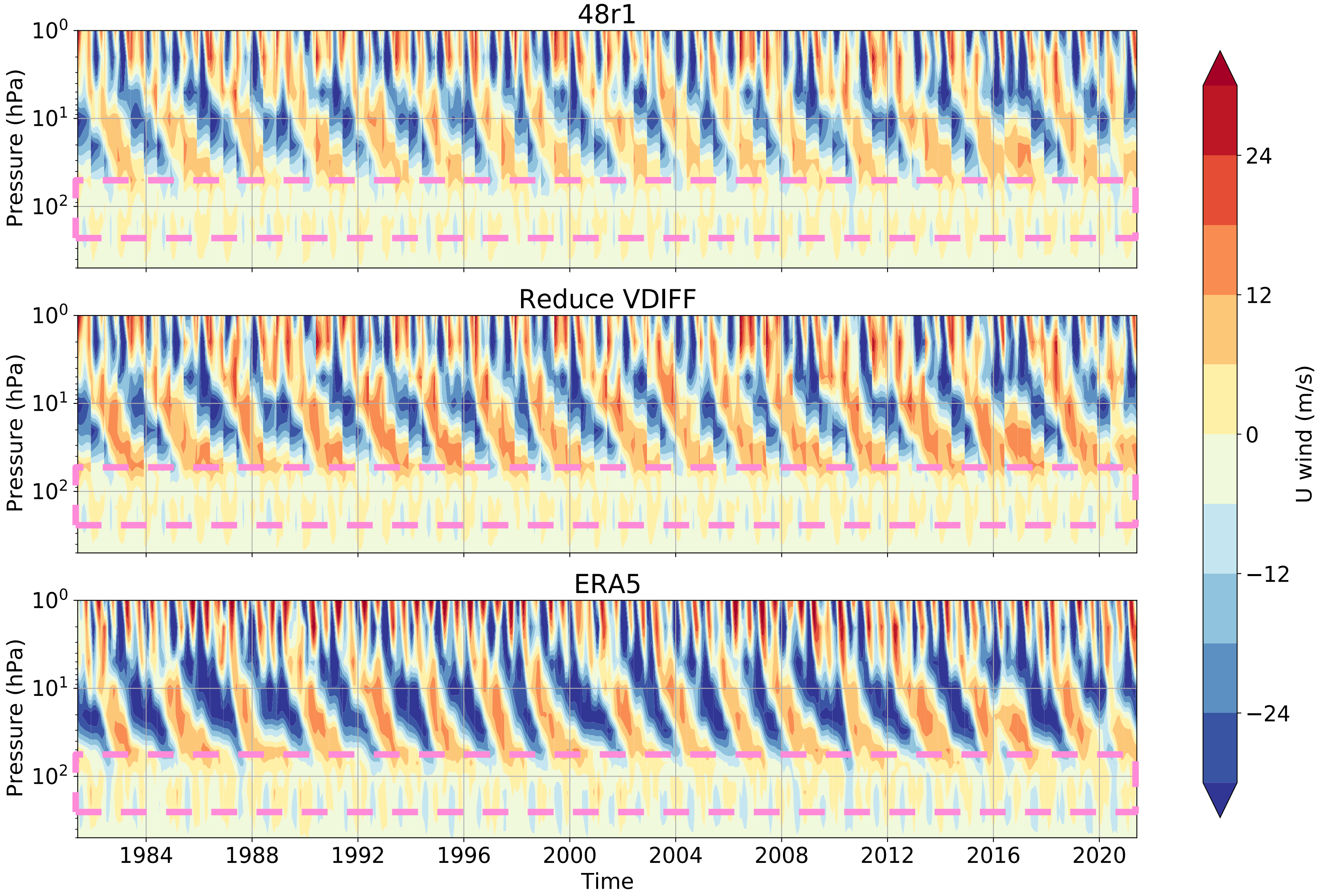

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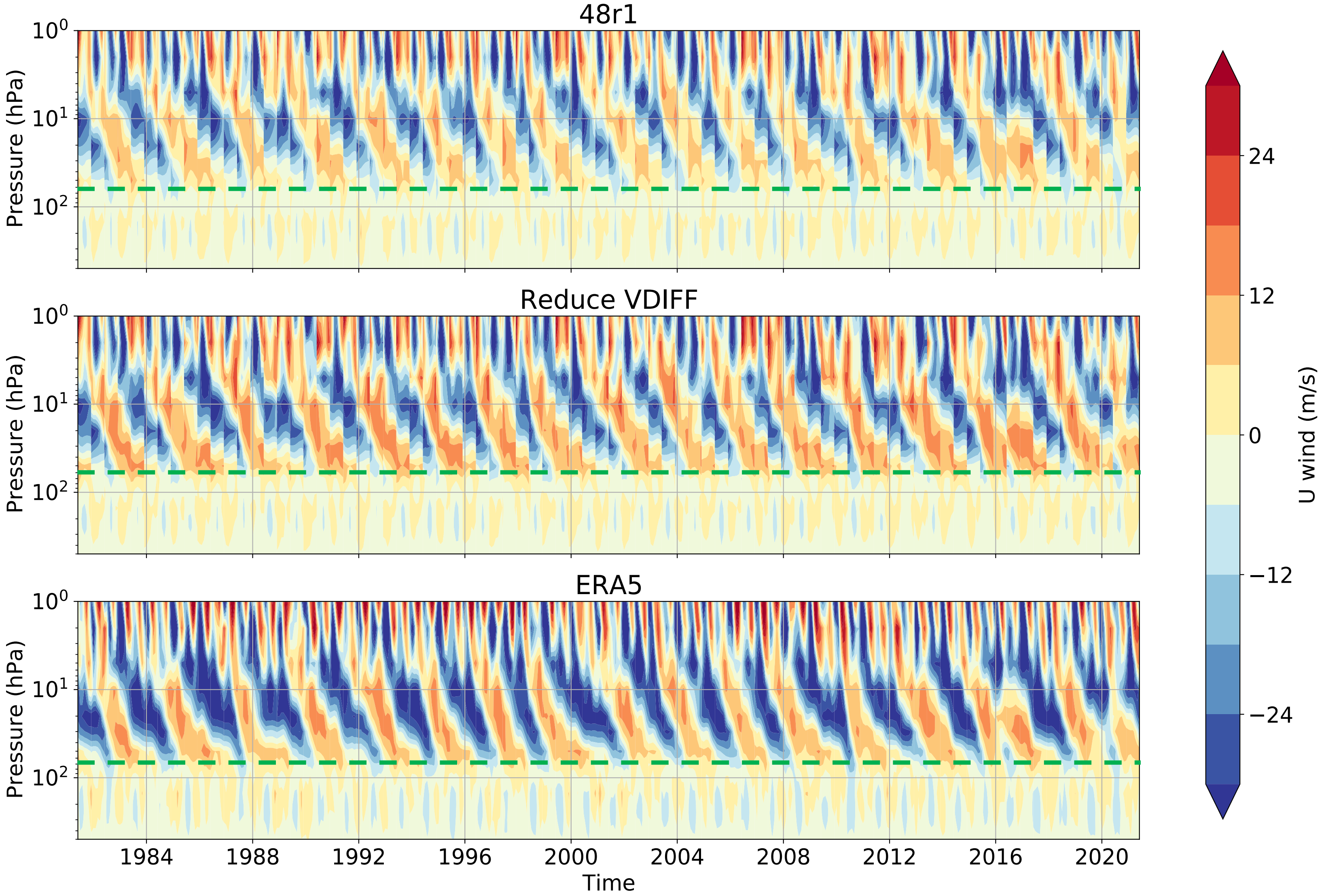
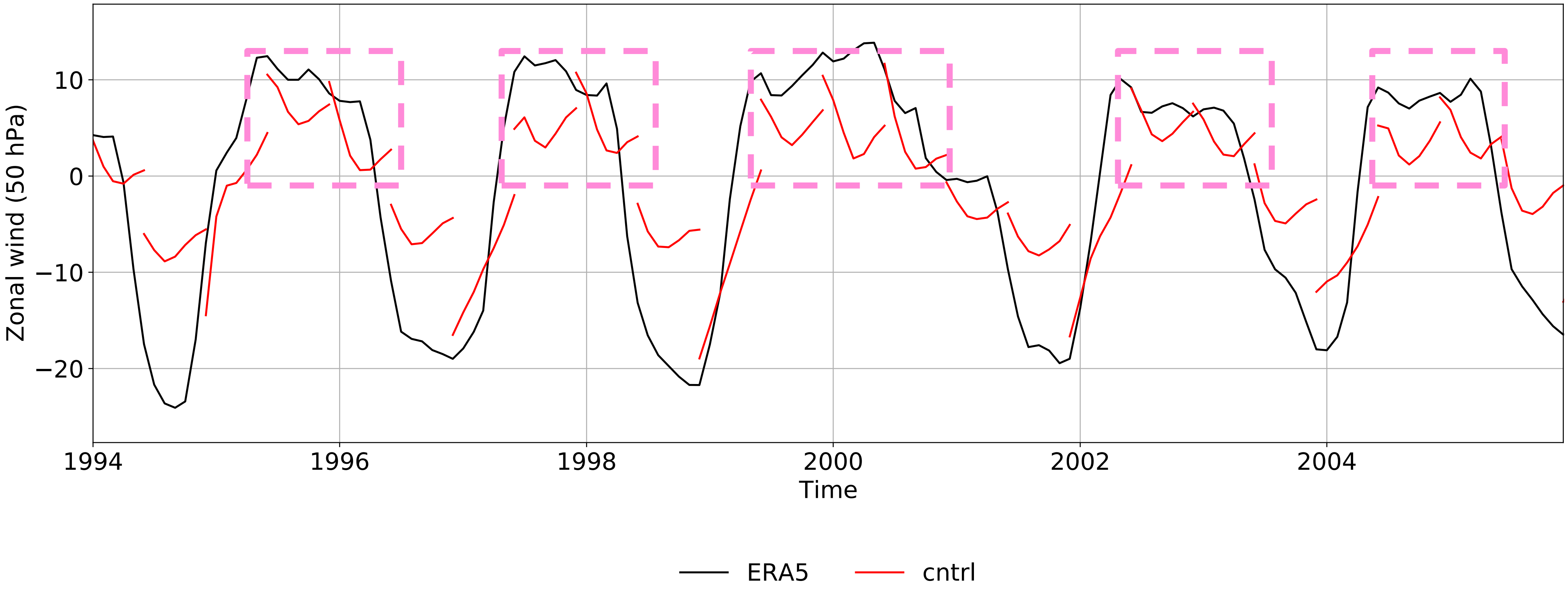


# Turbulent diffusion in the stratosphere

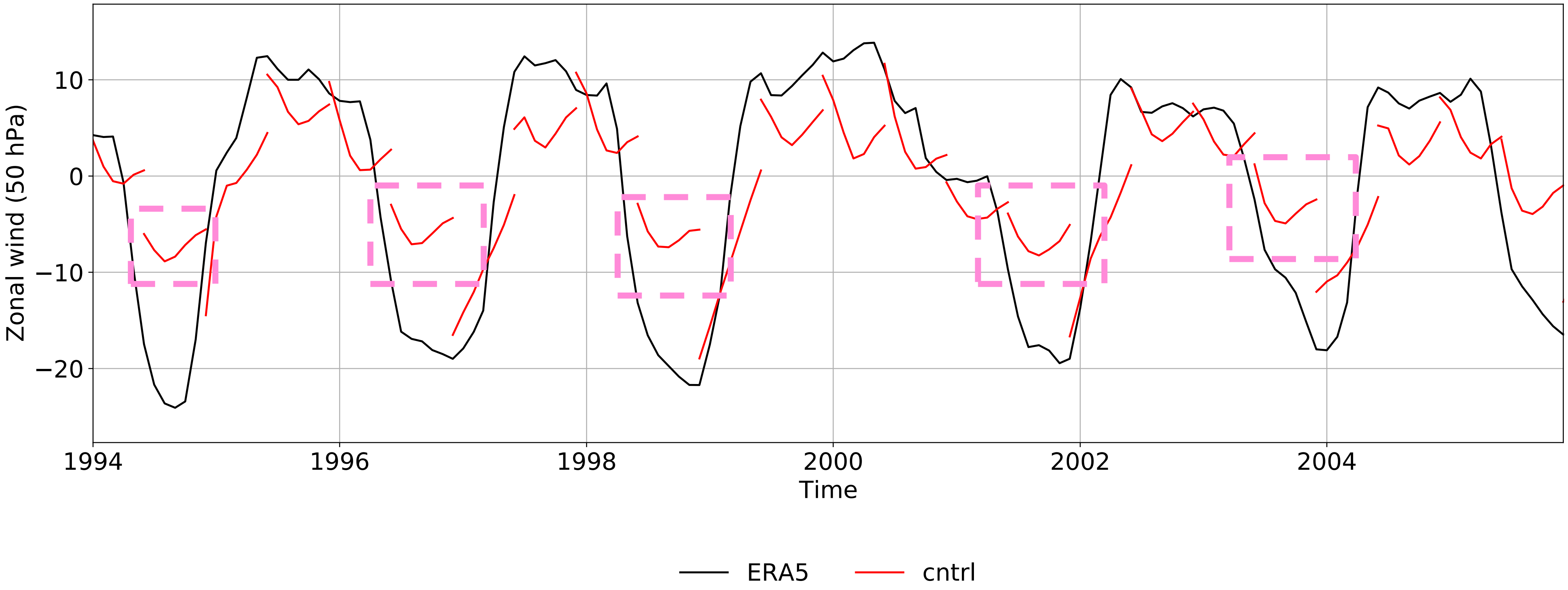
Current model has too weak winds in the QBO positive phase



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

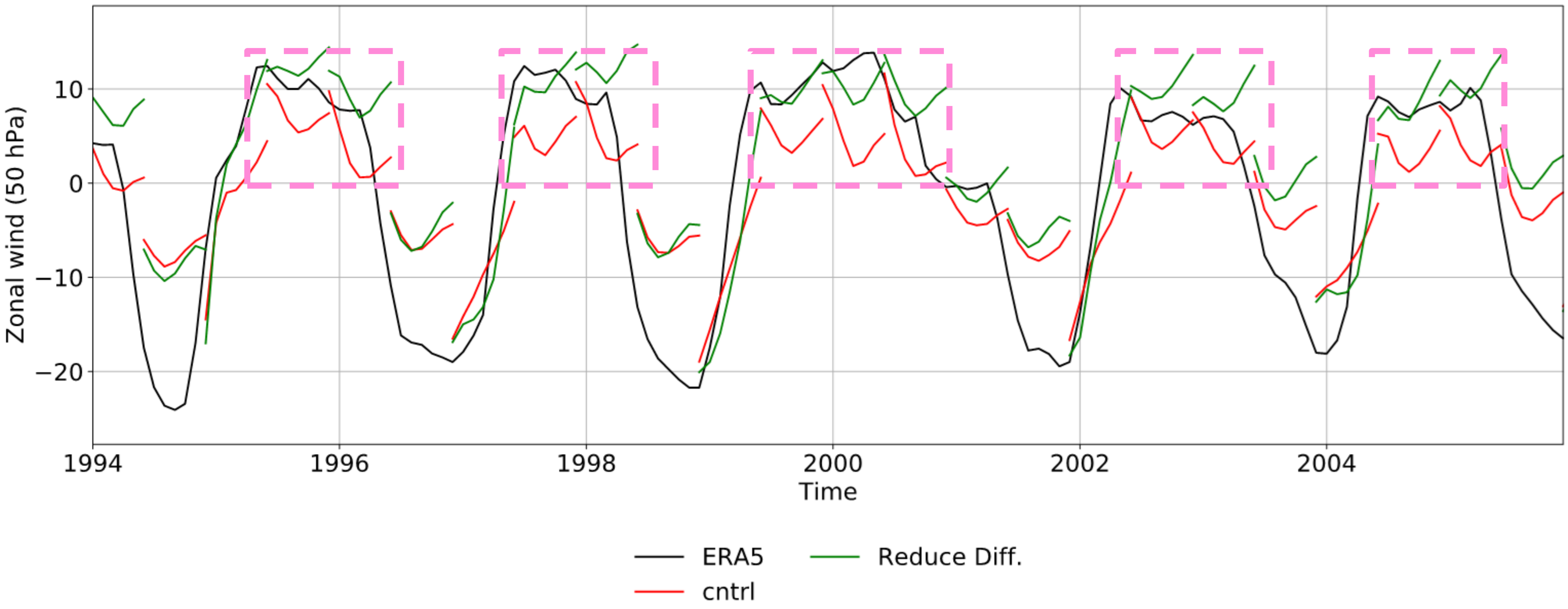


Plot shows 50 hPa zonal winds averaged between 5S – 5N

Seasonal hindcasts run with the ECMWF IFS, 7 months long

# Turbulent diffusion in the stratosphere

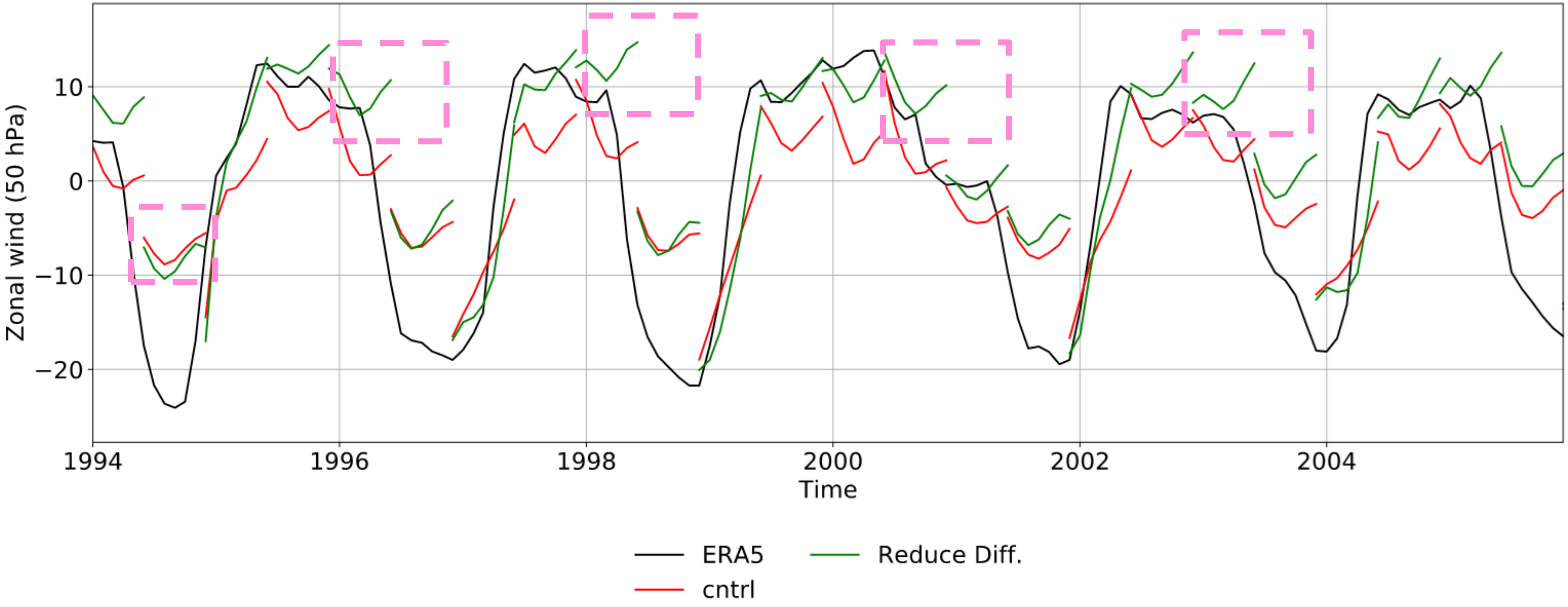
Reduced diffusion improves model winds in the QBO positive phase



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

# 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



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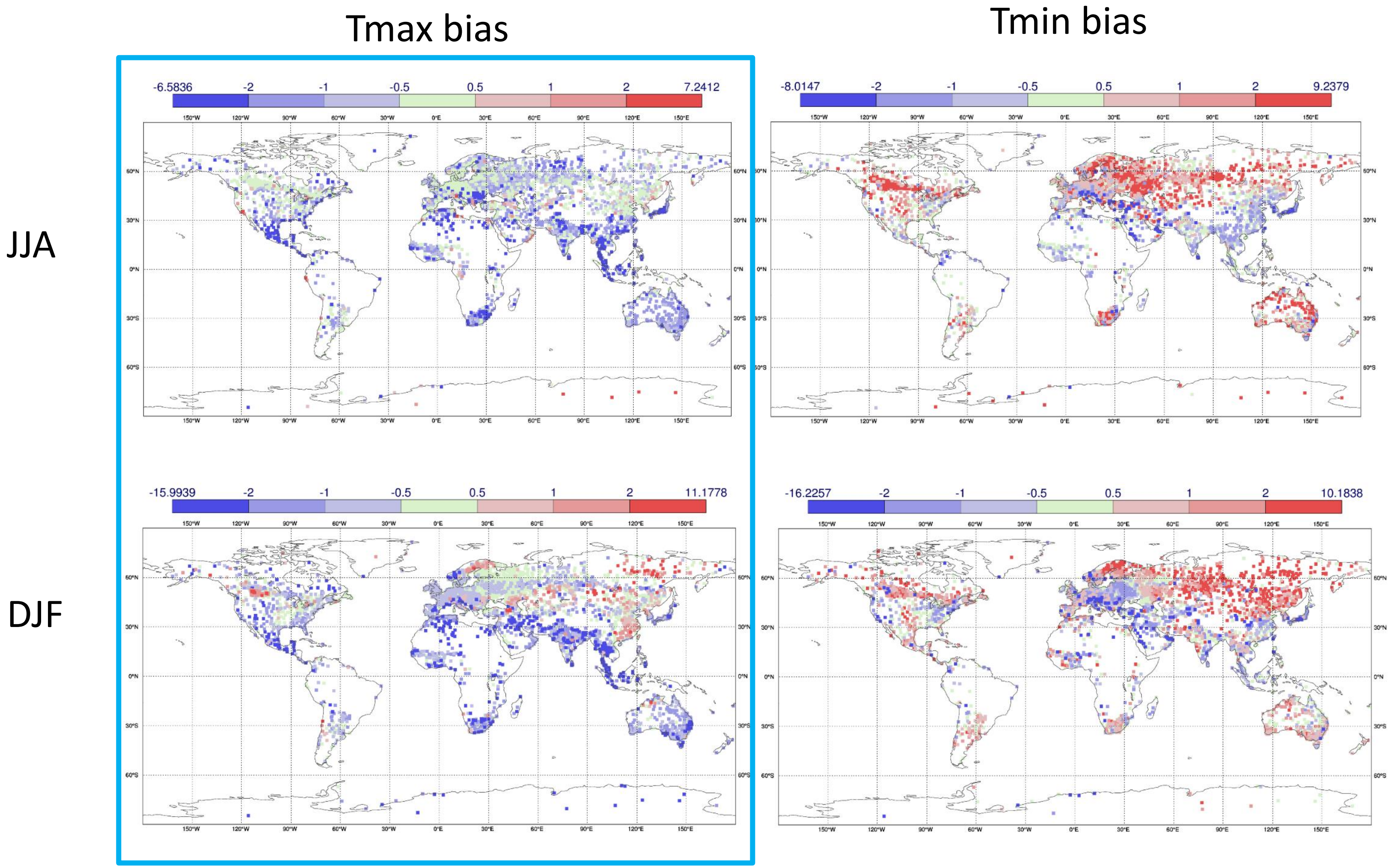
Seasonal hindcasts run with the ECMWF IFS, 7 months long

# Current near-surface model issues in stable boundary layers

# Near surface errors in stable conditions – 2m T

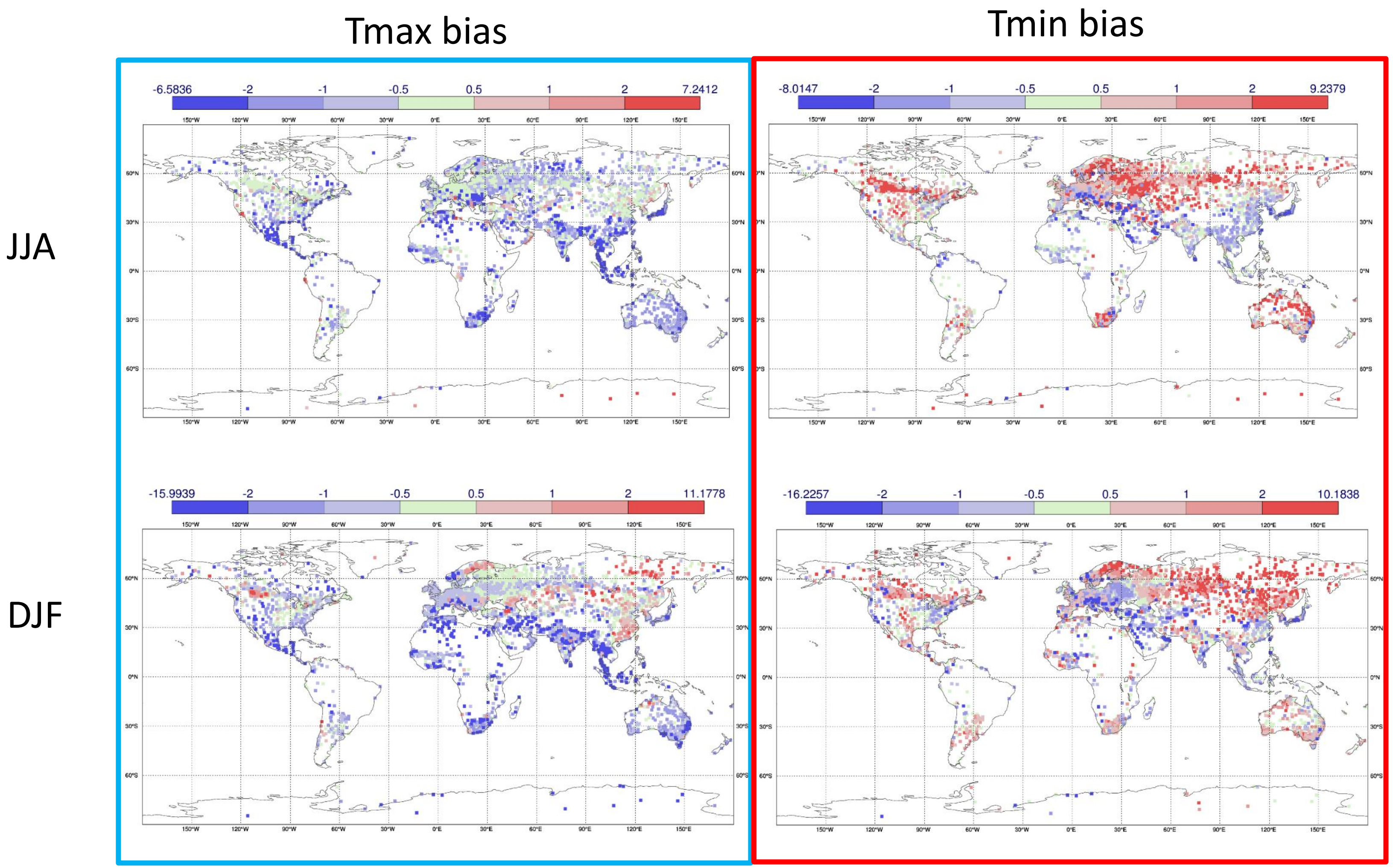


Sandu et al, 2020, ECMWF Tech memo 875

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



Sandu et al, 2020, ECMWF Tech memo 875

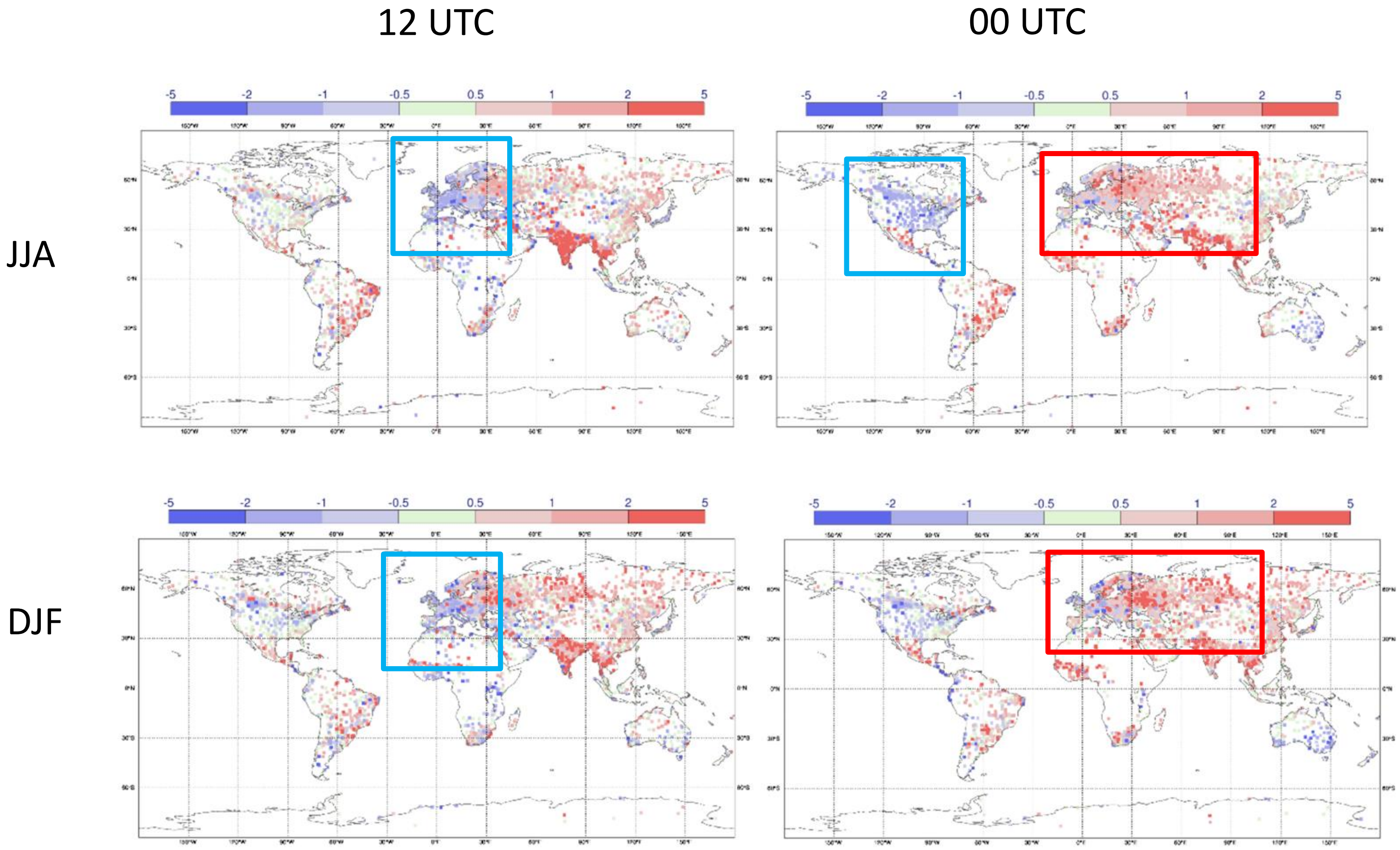
Plots show mean error of maximum (Tmax) and minimum (Tmin) 2m temperatures over 2018/2019 compared with SYNOP observations

Maximum (daytime) temperatures too cold

Minimum (nighttime) temperatures too warm

Mirrors the seasonal cycle

# Near surface errors in stable conditions – 10 UV



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

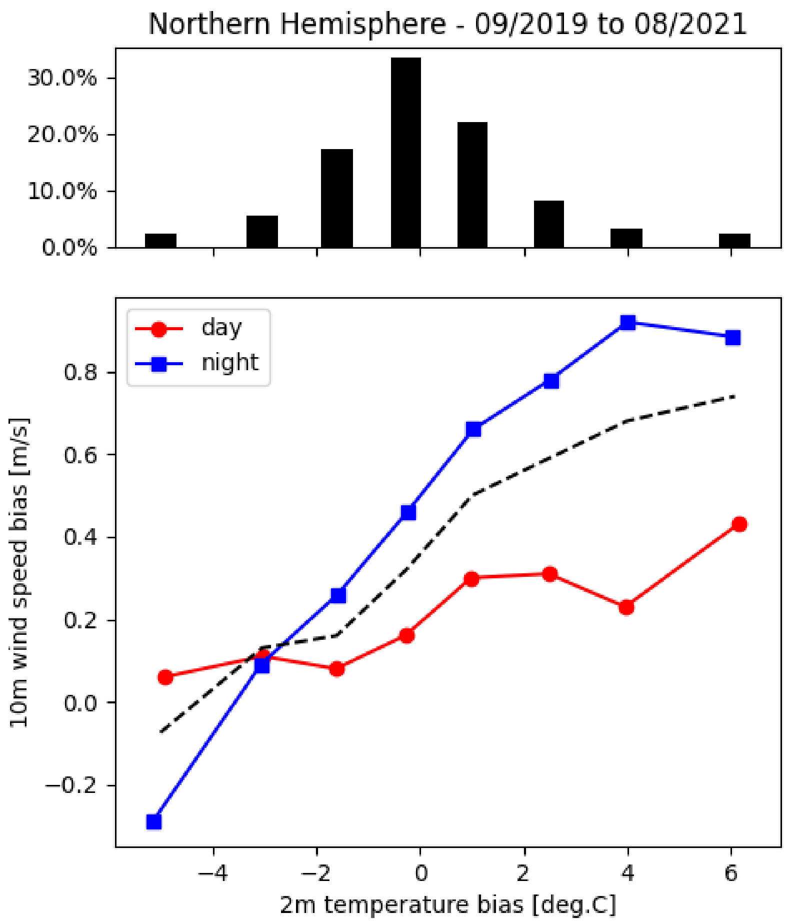
# Near surface errors in stable conditions

Temperature and wind errors largest at night

Wind and temperature errors are strongly correlated

Winds are too strong, 2m temperatures are too warm

Winds are too weak, 2m temperatures are too cold



Figures c/o Zied Bouallegue

Plots show binned mean bias of 10m wind and 2m temperature compared with SYNOP observations

# Near surface errors in stable conditions

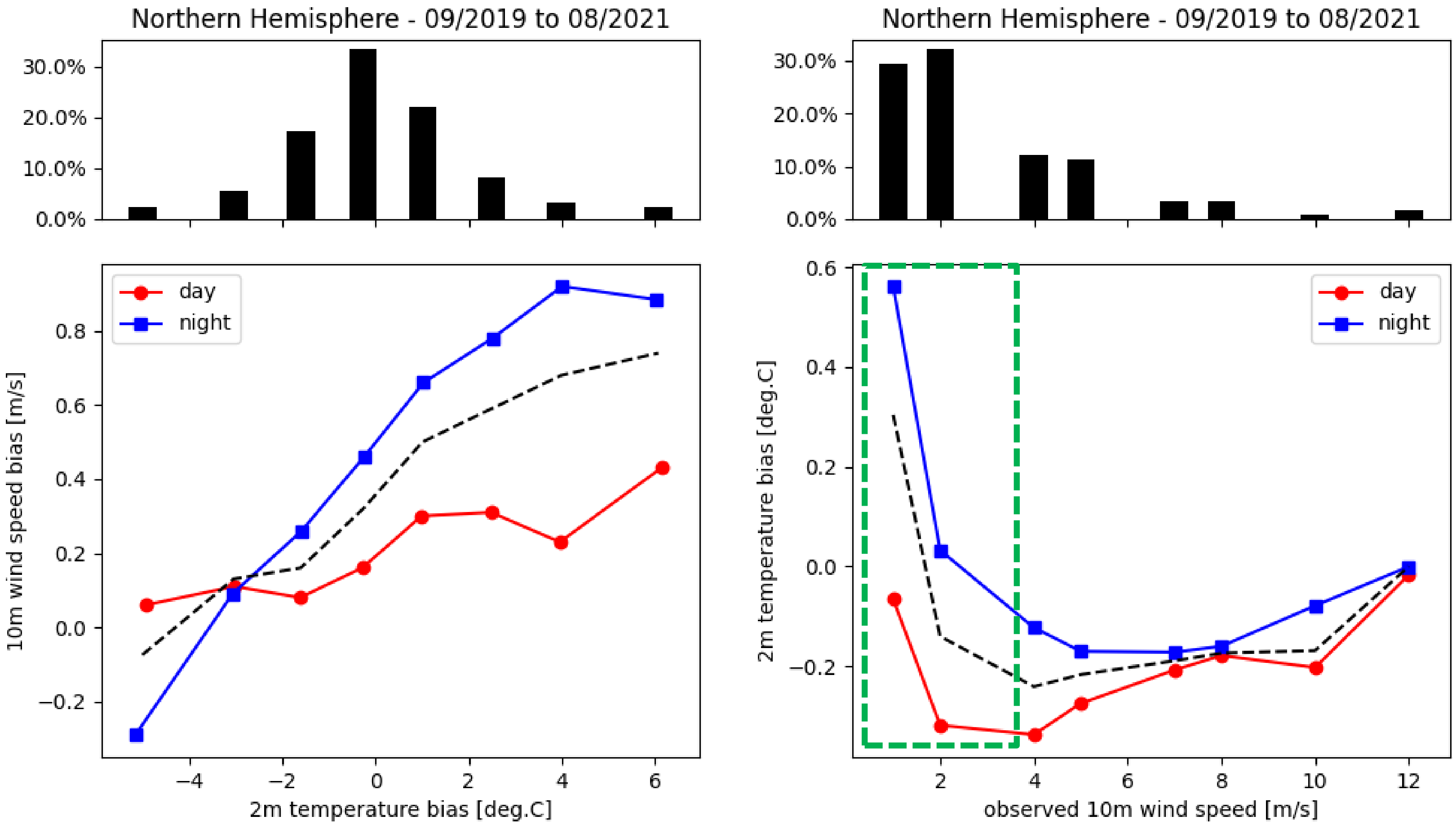
Temperature and wind errors largest at night

Wind and temperature errors are strongly correlated

Winds are too strong, 2m temperatures are too warm

Winds are too weak, 2m temperatures are too cold

Largest temperature errors in stable / weak wind conditions


Northern Hemisphere - 09/2019 to 08/2021

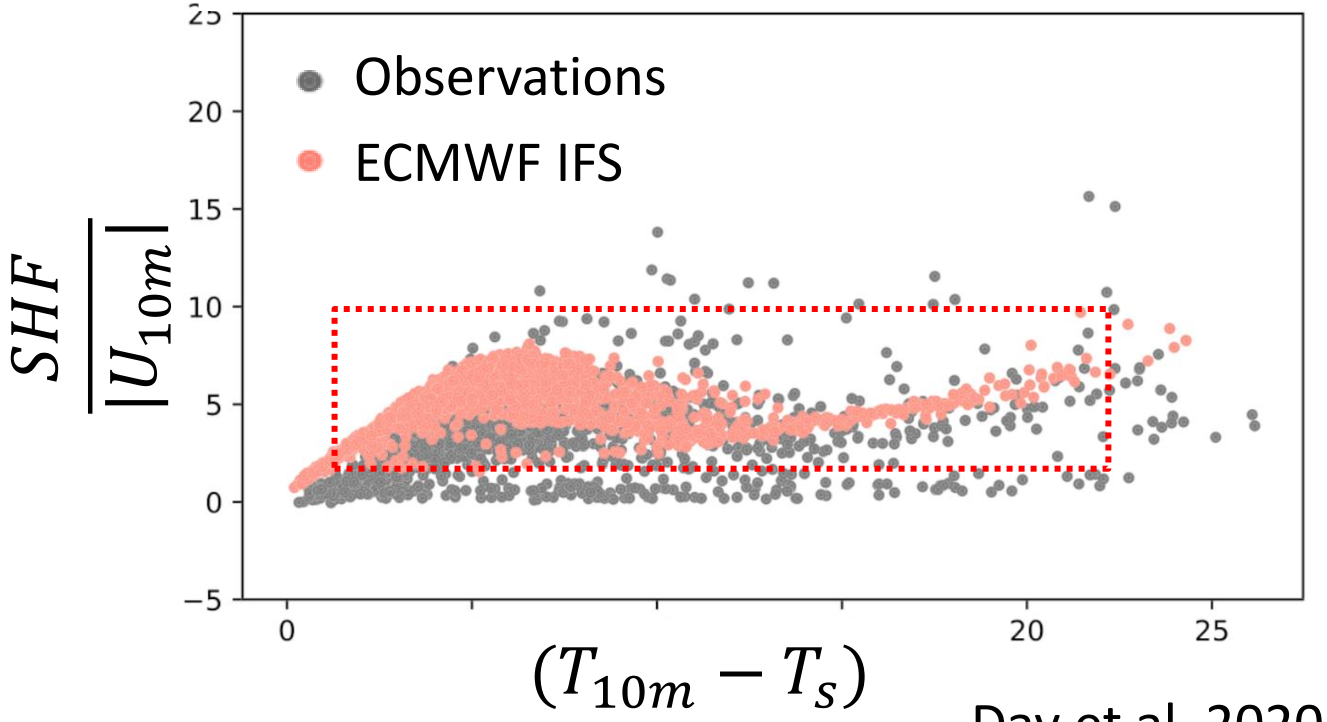
Northern Hemisphere - 09/2019 to 08/2021

Plots show binned mean bias of 10m wind and 2m temperature compared with SYNOP observations

Figures c/o Zied Bouallegue

# Too much turbulent mixing in stable conditions

Surface sensible heat flux
(Summit, greenland)



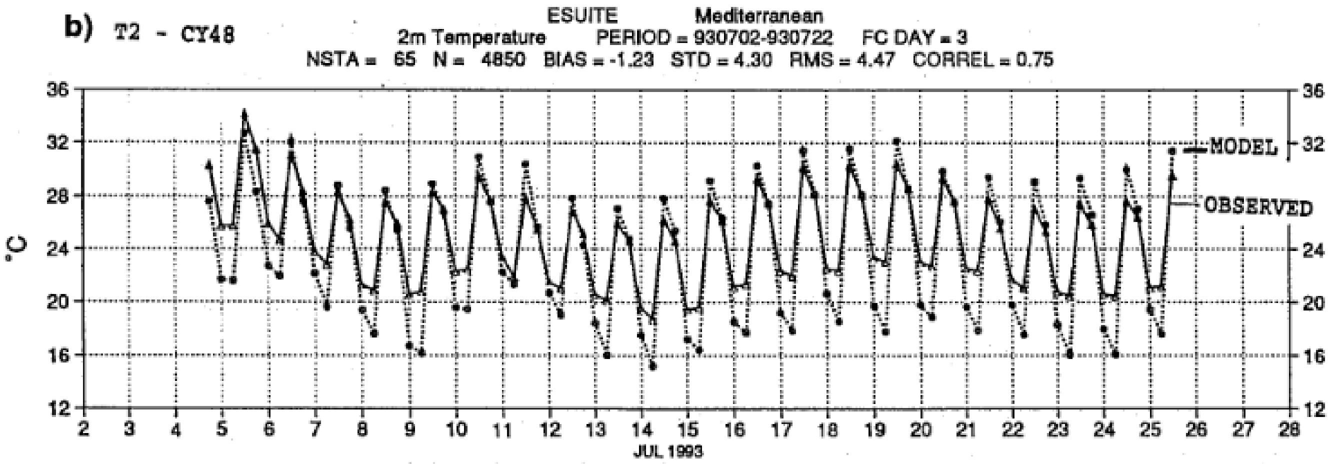
Day et al, 2020

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

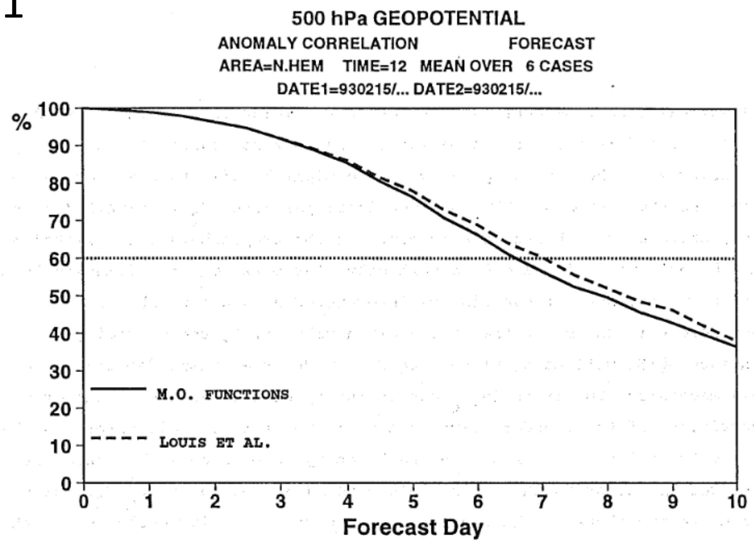
Comparison between model and observations suggest too much turbulent mixing in stable conditions

# Remember when there was not enough mixing?

Nighttime (stable regime) temperatures were too cold

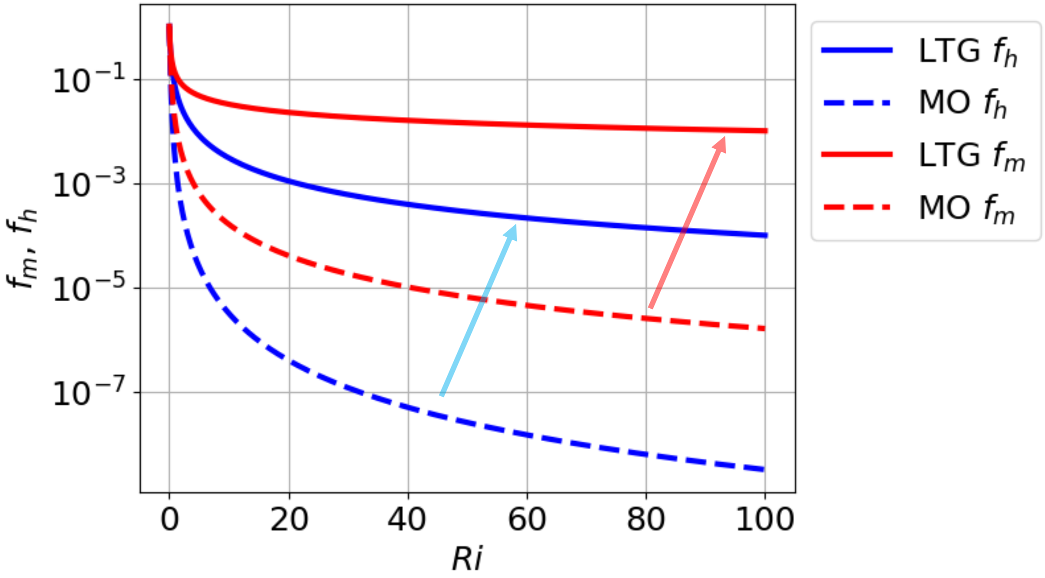


Beljaars, 1991



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

Mixing was increased in stable BLs

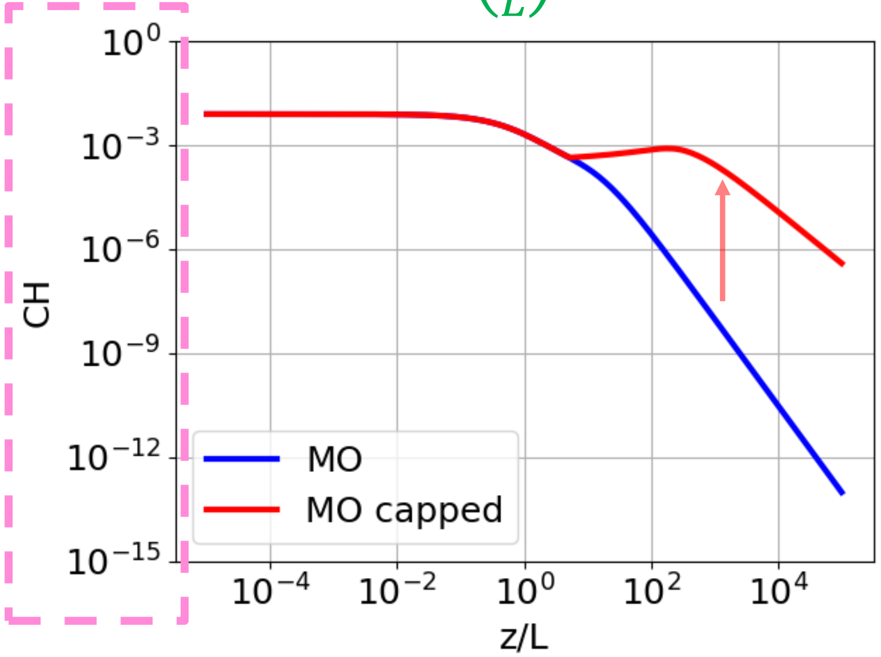


$$\overline{\theta' w'} \sim -l^2 \left|\frac{\partial \overline{u}}{\partial z}\right| \frac{\partial \overline{\theta}}{\partial z} f_H(Ri)$$

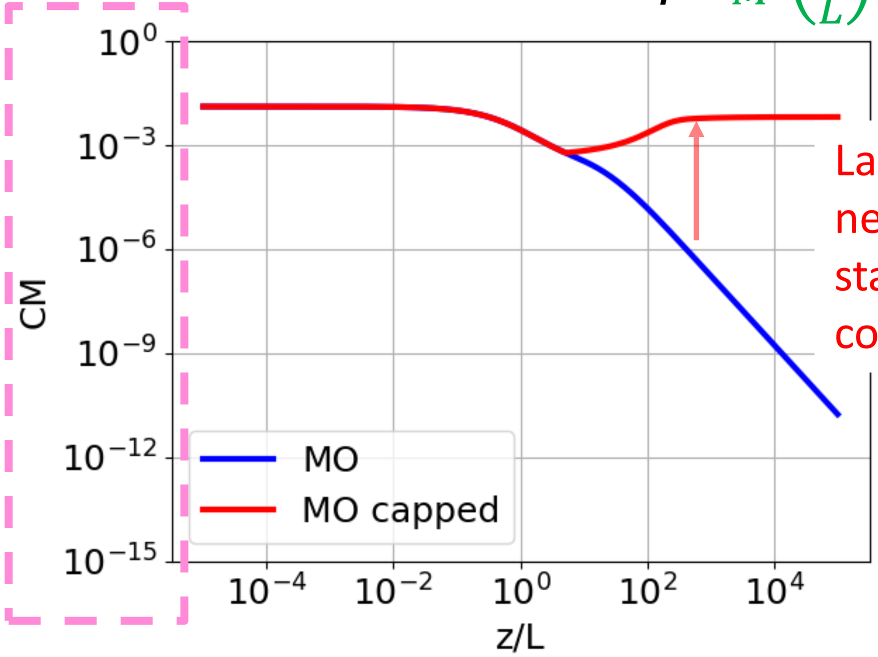
$$\overline{u' w'} \sim -l^2 \left|\frac{\partial \overline{u}}{\partial z}\right| \frac{\partial \overline{u}}{\partial z} f_M(Ri)$$

# What has happened since?

Heat flux $= \rho C_H\left(\frac{z}{L}\right)|U_n|(\theta_n - \theta_s)$



Momentum flux $= \rho C_M\left(\frac{z}{L}\right)|U_n|^2$



Large increase in near-surface mixing in stable / weak wind conditions

Cap imposed on $\frac{z+z_{0M}}{L}$:

if $\frac{z+z_{0M}}{L} > 5$, $\frac{z+z_{0M}}{L} = \frac{5L+z_{0M}}{L}$

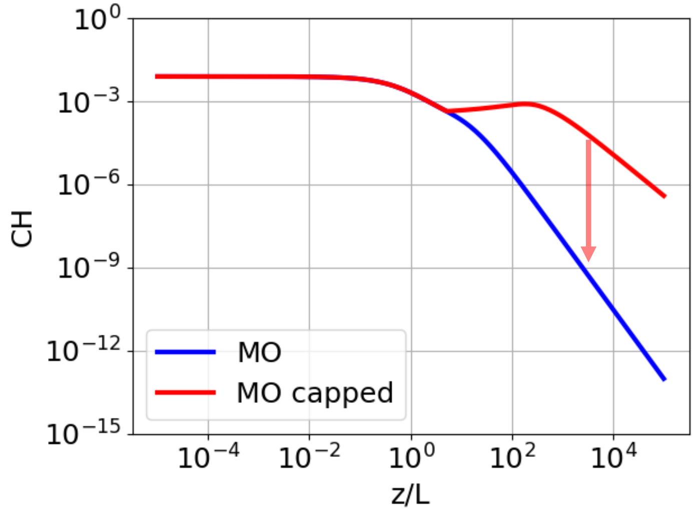
This is used to permit some minimum amount of mixing even in very stable conditions

But causes warm 2m T in stable conditions

Remember that $\frac{z+z_{0M}}{L}$ is buoyancy production / shear production

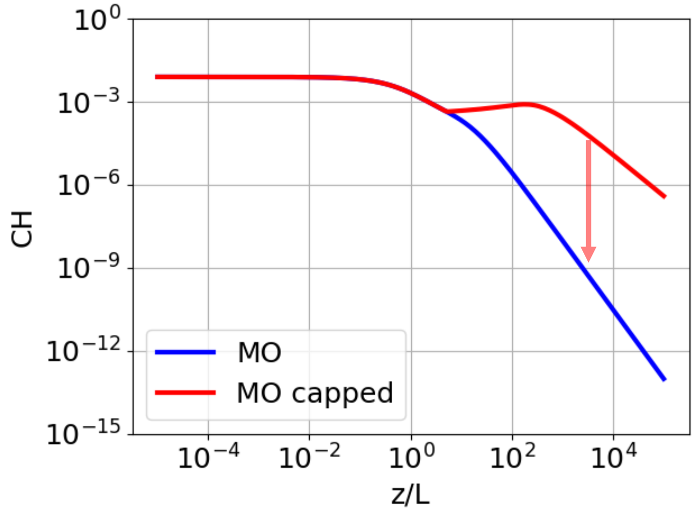
# Impact of removing $\frac{\mathrm{z}}{\mathrm{L}}$ limit: temperatures

Heat flux $= \rho C_H\left(\frac{z}{L}\right)|U_n|(\theta_n - \theta_s)$



# Impact of removing $\frac{z}{L}$ limit: temperatures

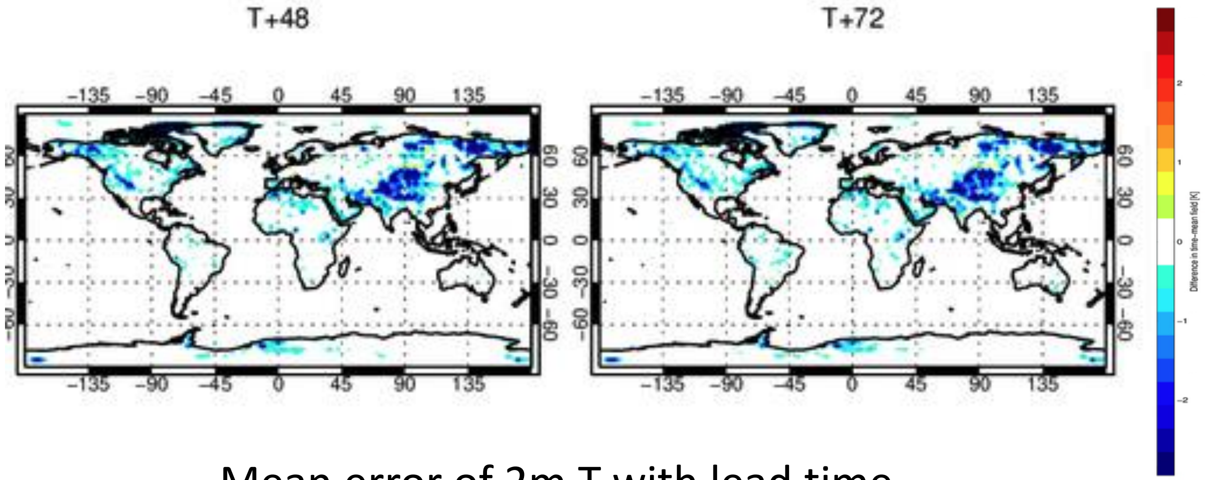
$$\text{Heat flux} = \rho C_H\left(\frac{z}{L}\right)|U_n|(\theta_n - \theta_s)$$



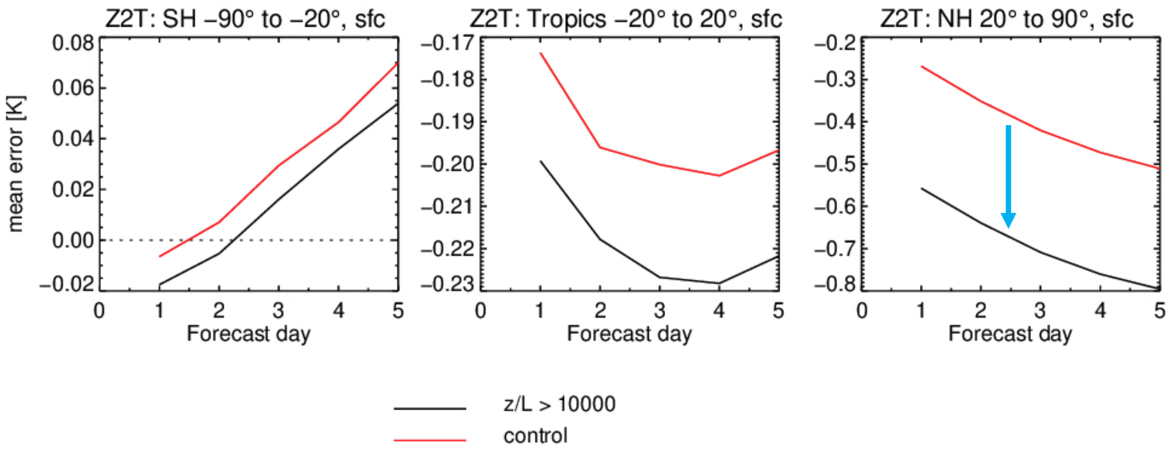
Does not work globally and leads to runaway cooling – especially over mountainous regions

Suggests that additional mixing is required in stable conditions, particularly over mountains (perhaps from processes other than turbulence)

Change in 2m T with lead time



Mean error of 2m T with lead time

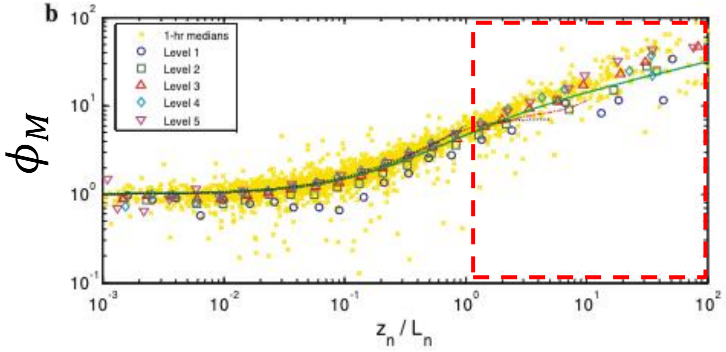


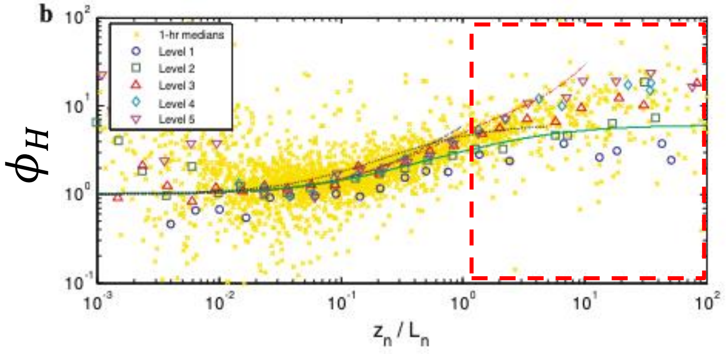
# Empirical stability functions Cookbook –
## SHEBA site

- Ingredients:
  - Accurate surface layer fluxes ($\overline{u'w'}, \overline{\theta'w'}$)
  - Wind and temperature profiles at several heights
  - Wide range of sampled stability

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

Note that $\frac{z}{L}$ stopped at 2 in Businger et al (1970)





# 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

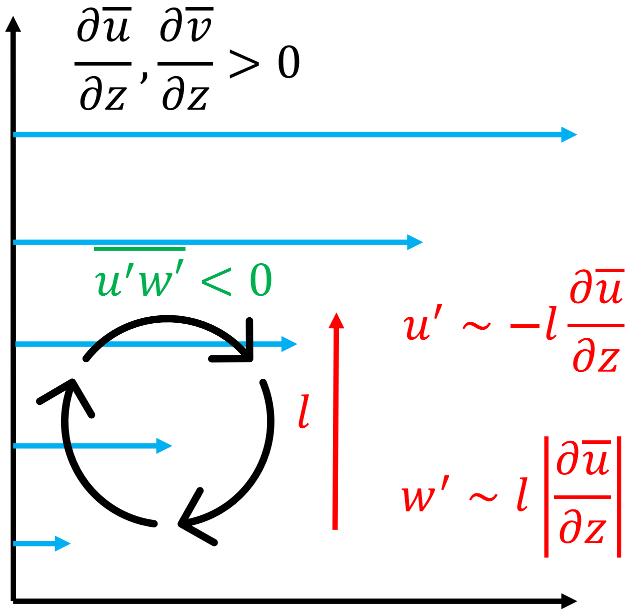
# ‘Local’ turbulence closure: eddy diffusion above the surface

## 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

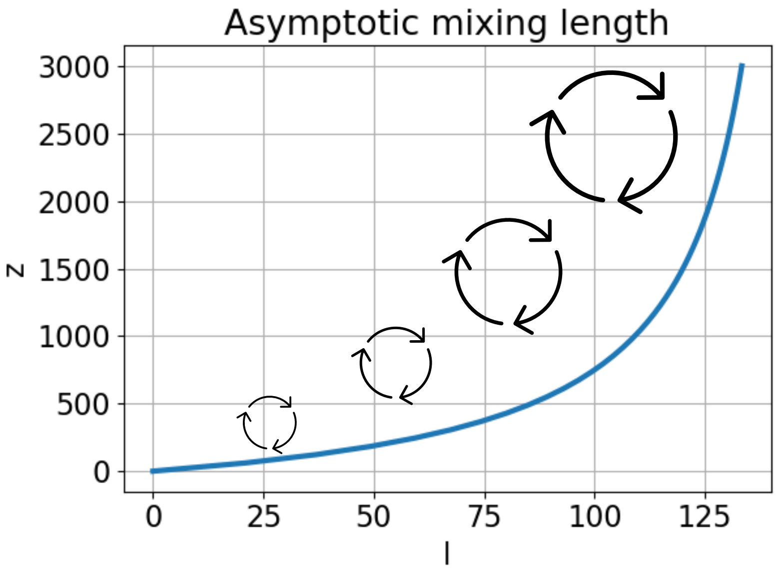
$$\overline{\theta'w'} \sim -K_H \frac{\partial \overline{\theta}}{\partial z} = -l^2 \left|\frac{\partial \overline{u}}{\partial z}\right| f_H(Ri) \frac{\partial \overline{\theta}}{\partial z}$$



Size of eddies get larger further away from the surface:

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

$\kappa$ =von-Karman constant
$\lambda$ =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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Thermodynamics

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

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

$C_k, C_3$ - closure constants

Stability functions $\chi_3\left(Ri_f^*\right)$, $\phi_3\left(Ri_f^*\right)$- 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:

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

Buoyancy production

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

Shear production:

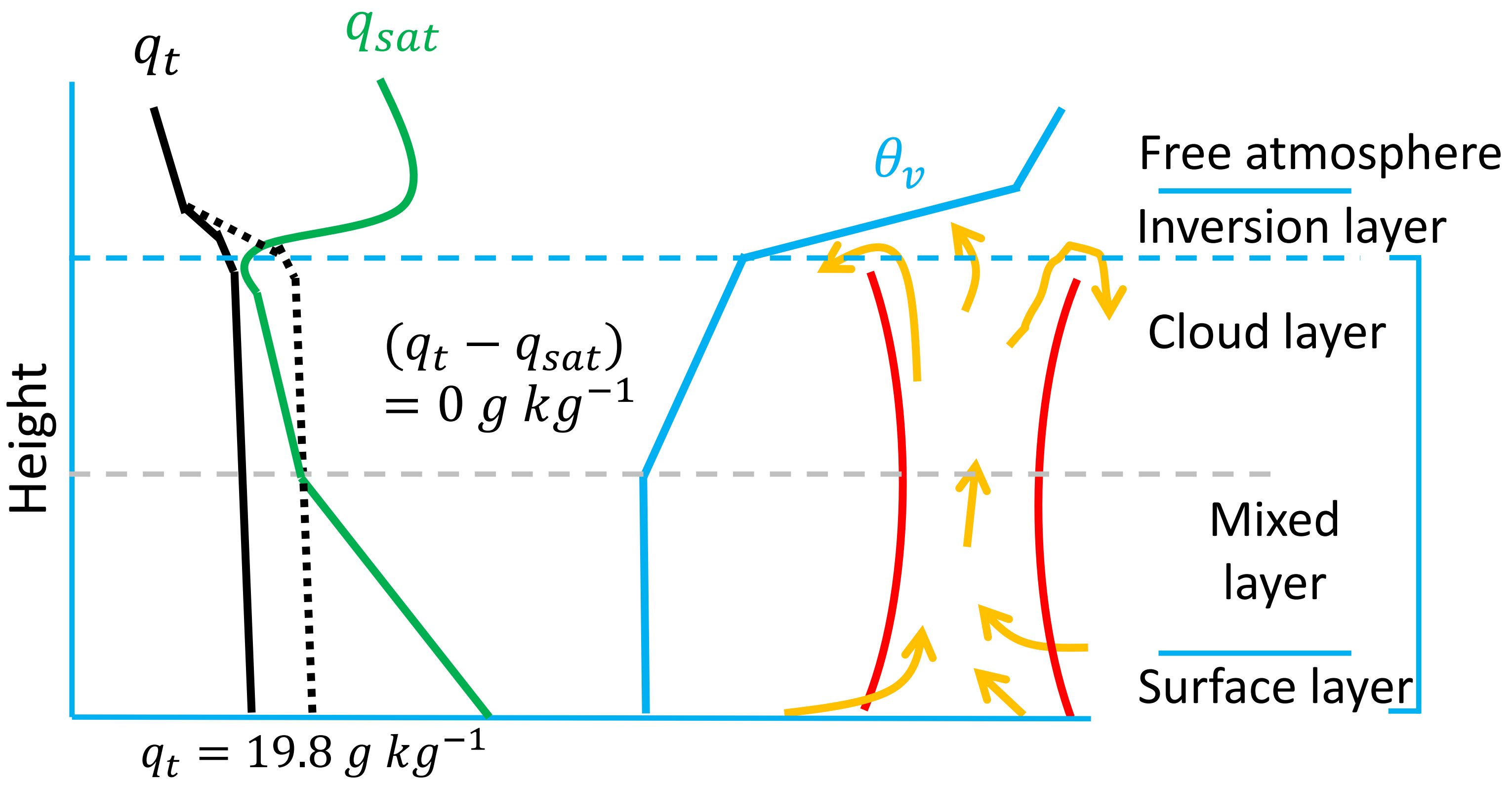
$$ST = -\overline{u'w'}\frac{\partial u}{\partial z} - \overline{v'w'}\frac{\partial v}{\partial z} \approx \mathrm{K_M}\left|\frac{\partial u}{\partial z}\right|$$

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



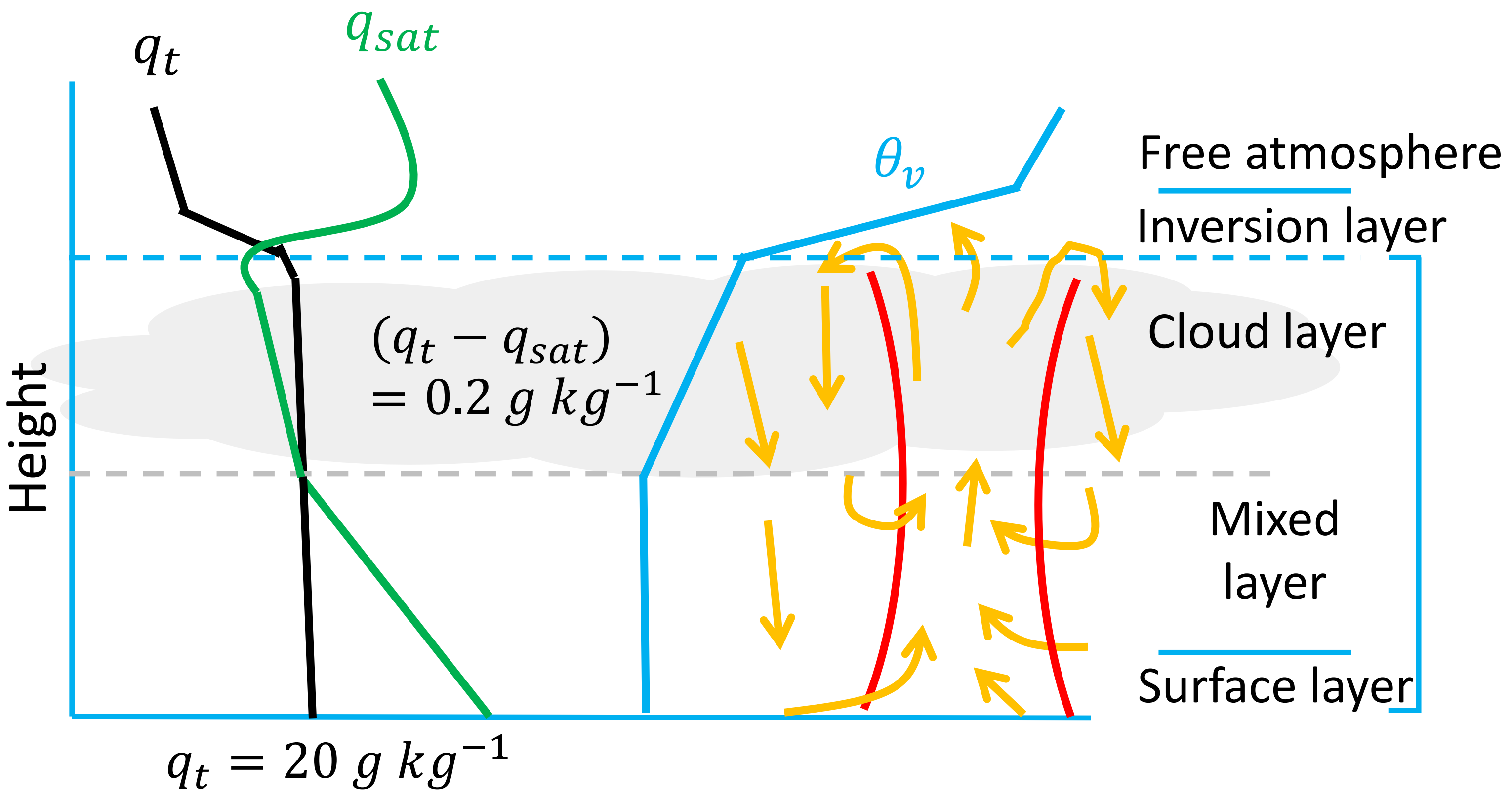
The presence of stratocumulus is sensitive to:

- 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

# 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:

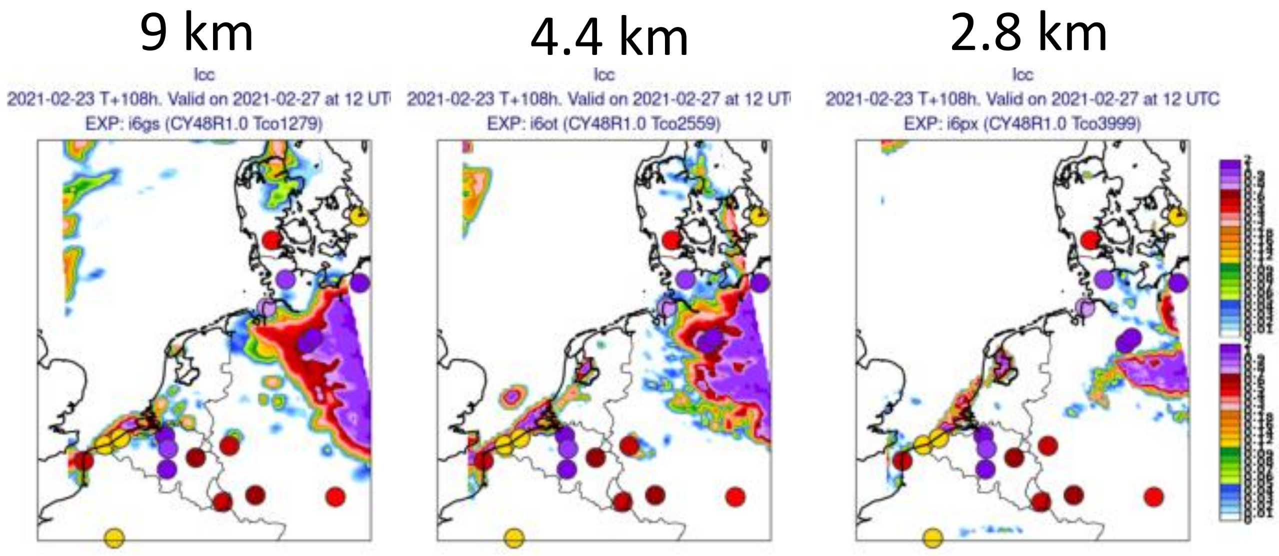
- Stronger entrainment from free atmosphere
- Condensation within cloud
- Radiative heating/cooling, which is essential for cloud evolution

# Impact of TKE on low level clouds

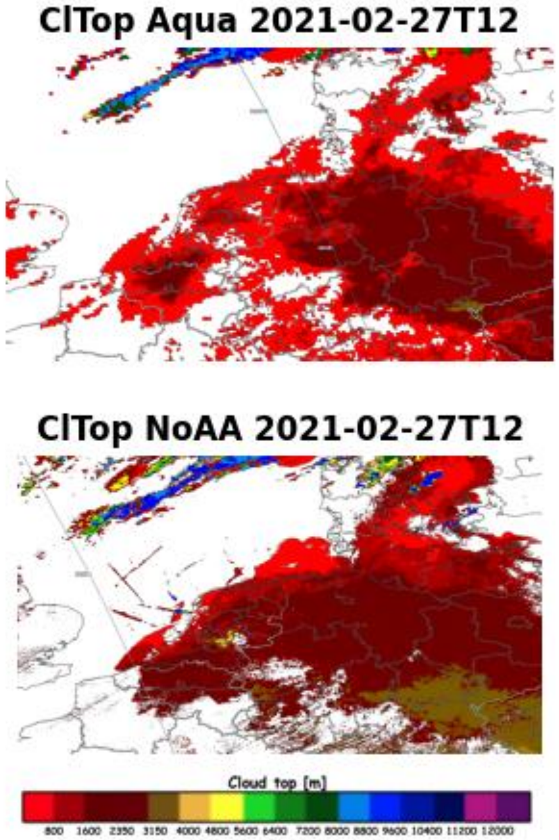
Current turbulence scheme underestimates low cloud cover

Horizontal resolution

CY48R1.0



Observation of cloud top height



Figures c/o Ivan Bastak-Duran

# Impact of TKE on low level clouds

Current turbulence scheme underestimates low cloud cover

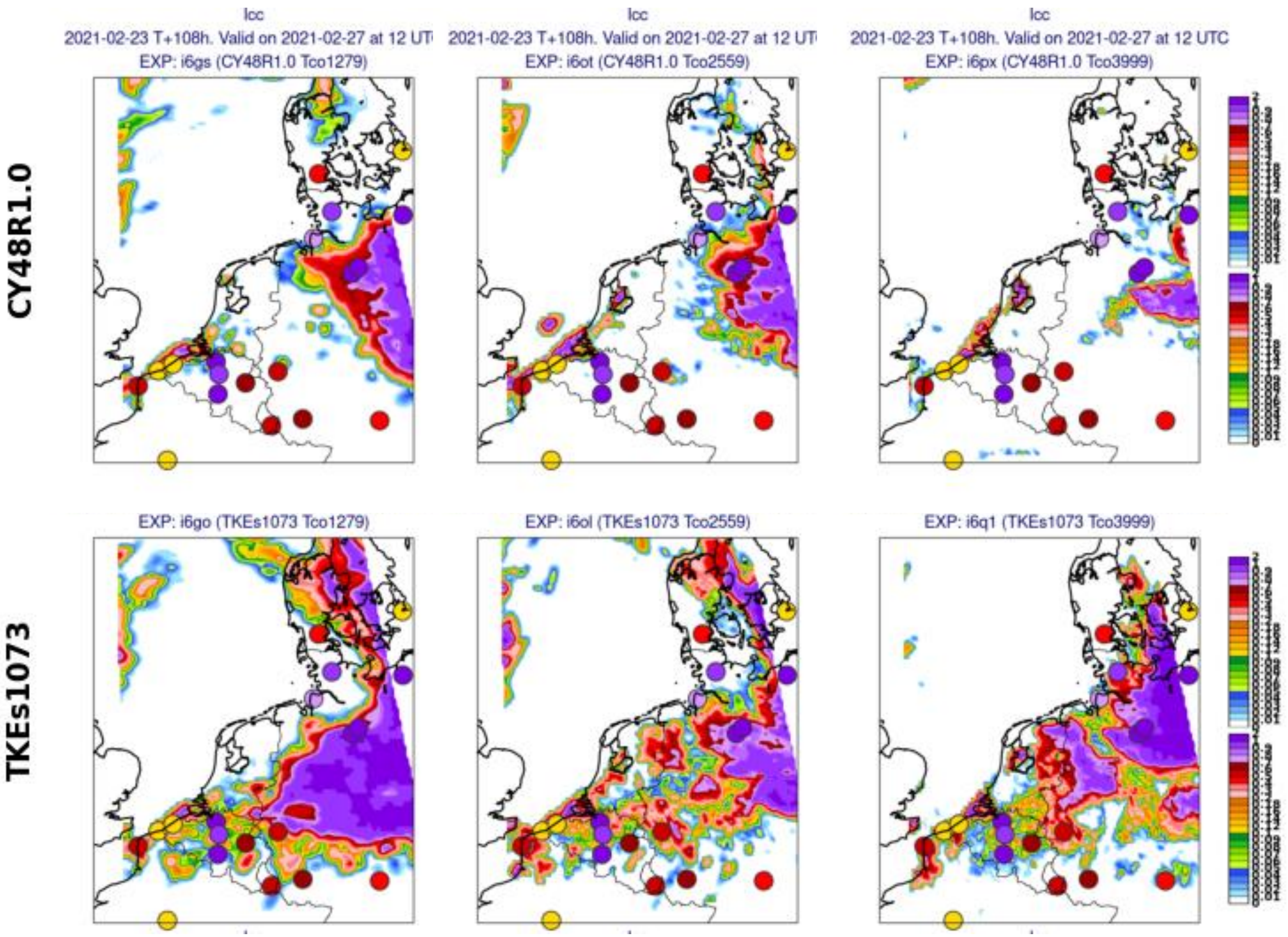
TKE scheme tends to have less mixing in these cases, and so can maintain low cloud

Horizontal resolution

9 km

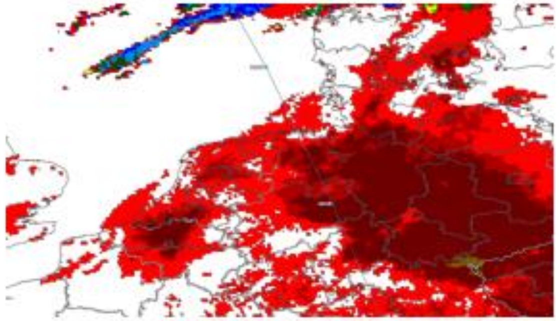
4.4 km

2.8 km

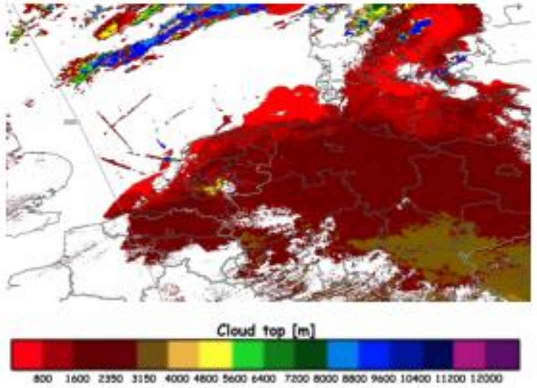


Observation of cloud top height

**ClTop Aqua 2021-02-27T12**



**ClTop NoAA 2021-02-27T12**



Figures c/o Ivan Bastak-Duran

# Impact of TKE on low level clouds

Current scheme cannot maintain low cloud – mixed too rapidly

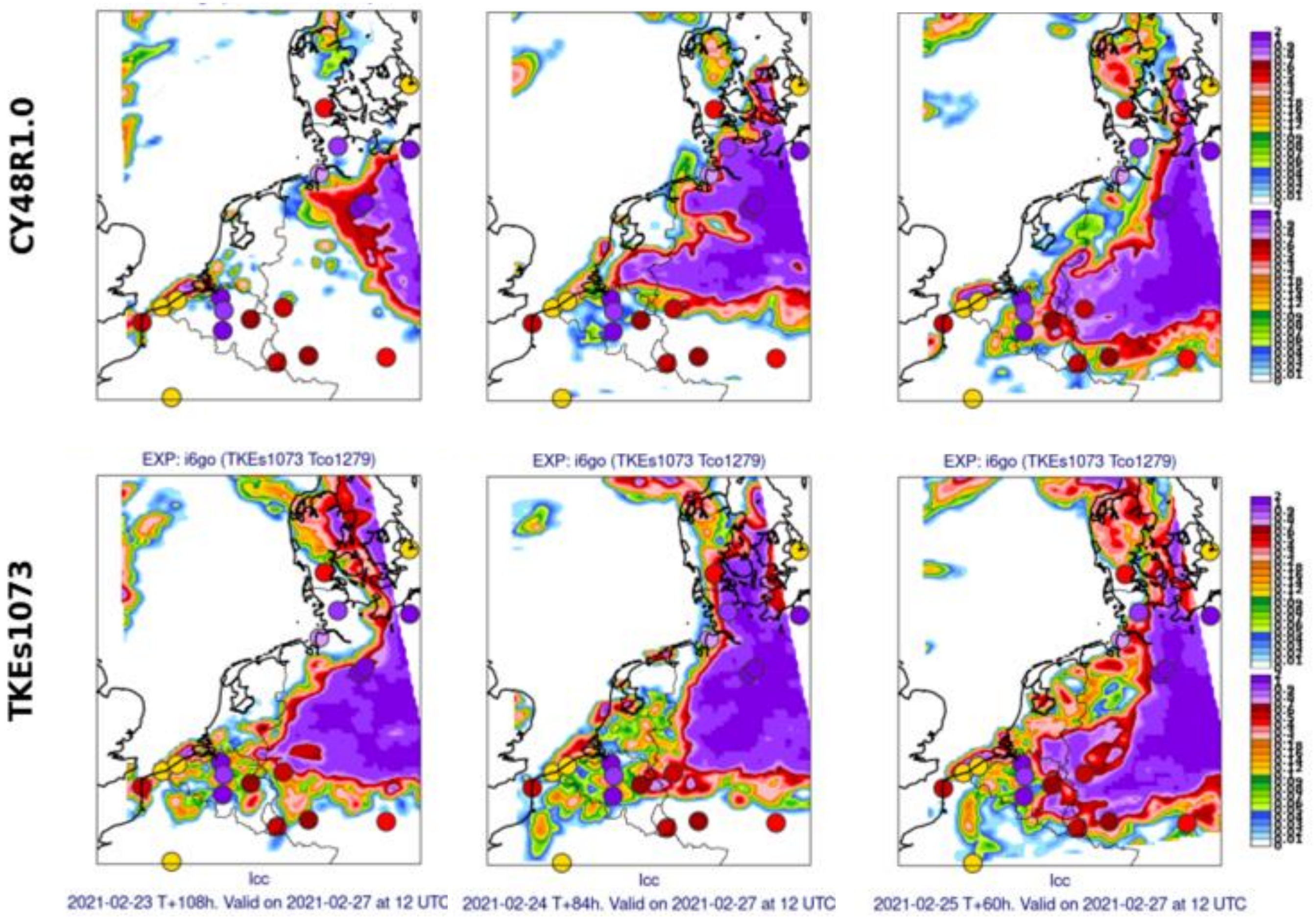
TKE scheme has low cloud even at a lead time of 3 days

Forecast lead time

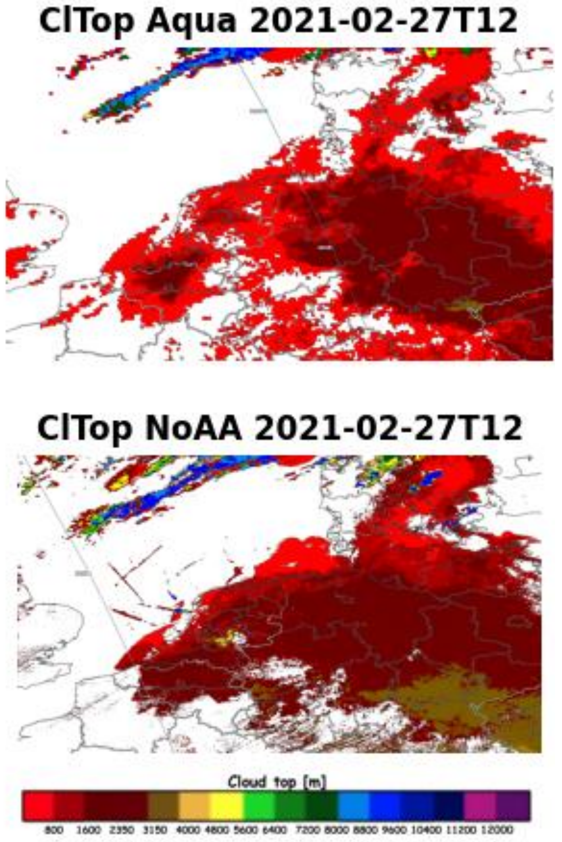
3 days

2 days

1 day



Observation of cloud top height



Figures c/o Ivan Bastak-Duran

# Summary of BL parametrization

- **Empirical stability functions:**
  - Functions used to relate the fluxes and gradients are highly empirical
  - Uncertainty (especially in stable regimes) means they are sometimes ‘tuned’
- **IFS parametrization:**
  - Due to the uncertainty in the stability functions, different forms are used throughout the atmosphere
  - EDMF is used in unstable BLs below cloud top
- **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