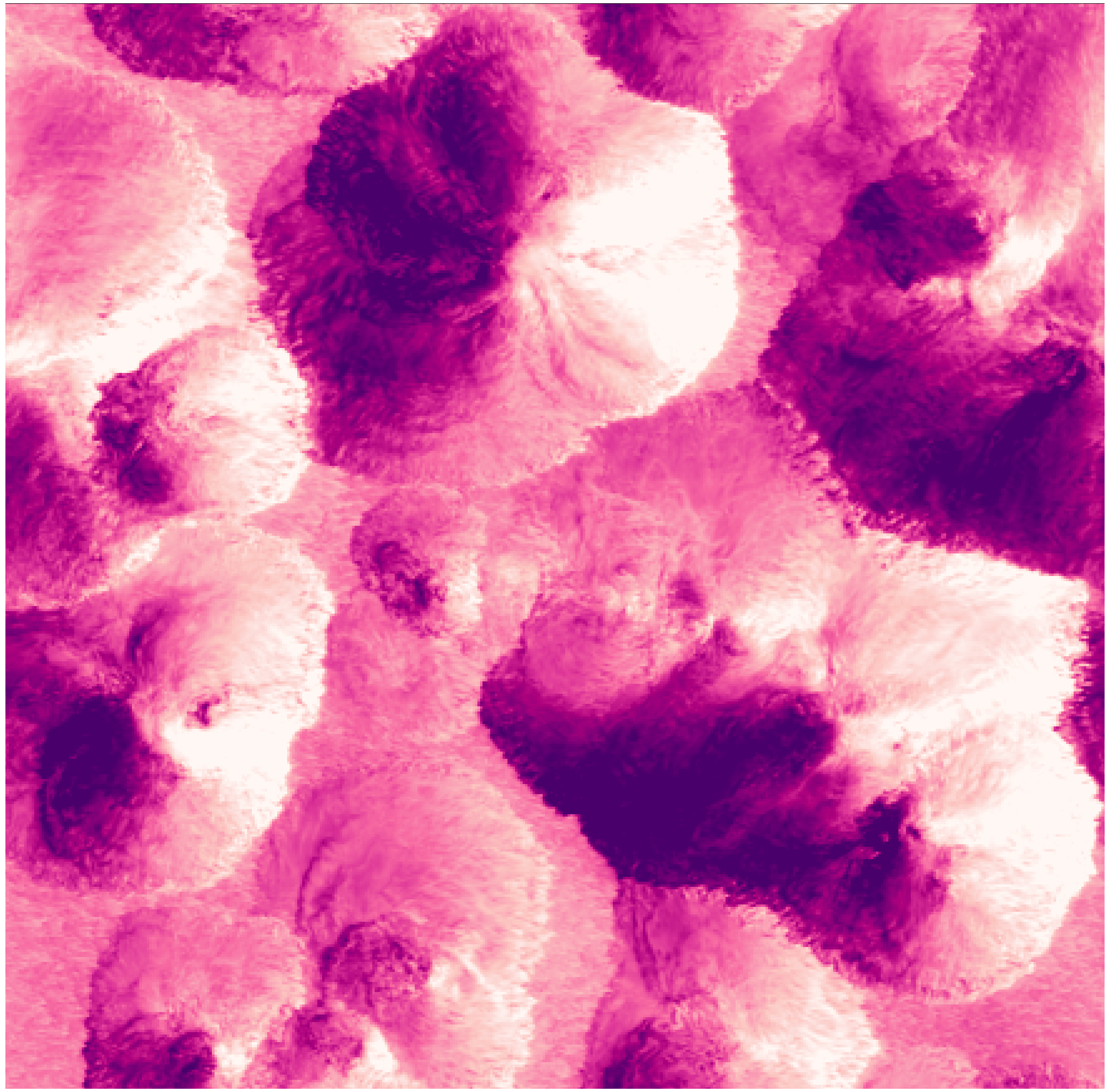
Momentum transport across scales in complex cloudy atmospheres

Louise Nuijens, Alessandro Savazzi, Vishal Dixit, Pier Siebesma, Wim de Rooy

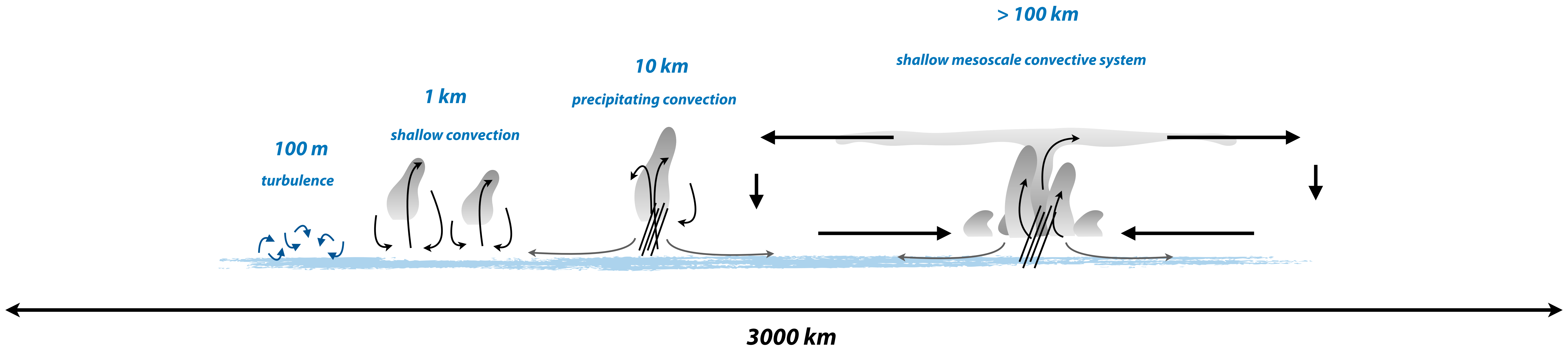
ECMWF Annual Seminar
September 12, 2022



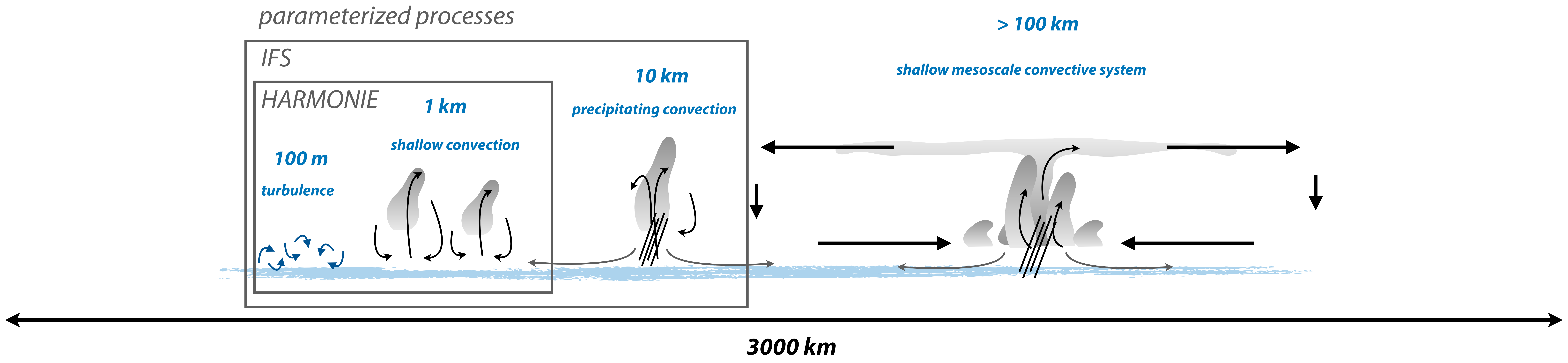
Flowers in the wind, by Alessandro Savazzi

Myriad of shallow convective clouds across the North Atlantic

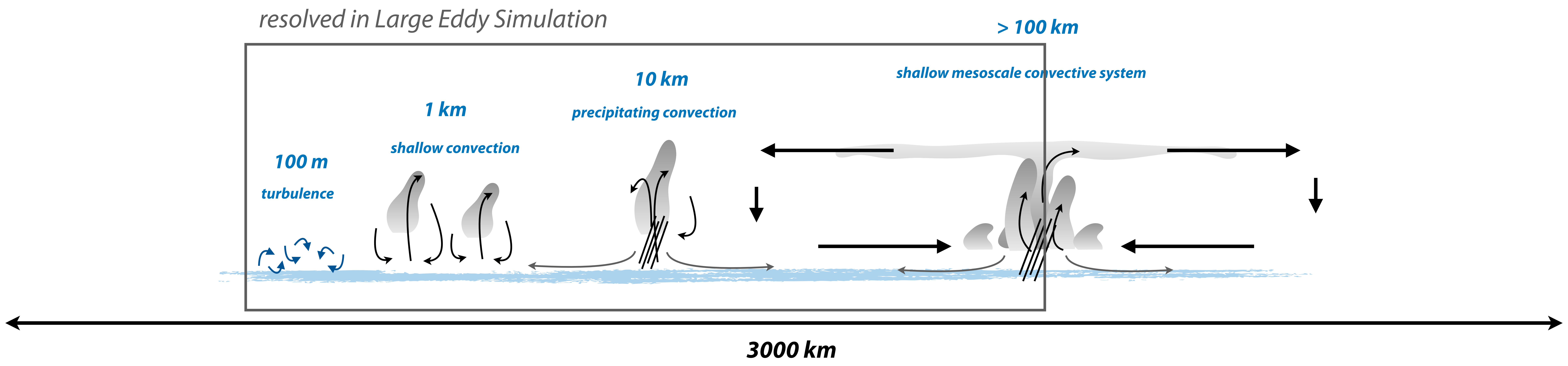
Multi-scale flows in the presence of shallow cloud organization patterns



Turbulence and shallow convection parameterized in weather models



From idealised to realistic large-eddy simulation run in 'weather' mode



What have we learned about shallow convective momentum transport?

1. Down-gradient and up-gradient momentum transport - since the 90's
2. Convective momentum transport in Large Eddy and Storm Resolving Models: relevant scales
3. Link to wind biases in the IFS in the trades

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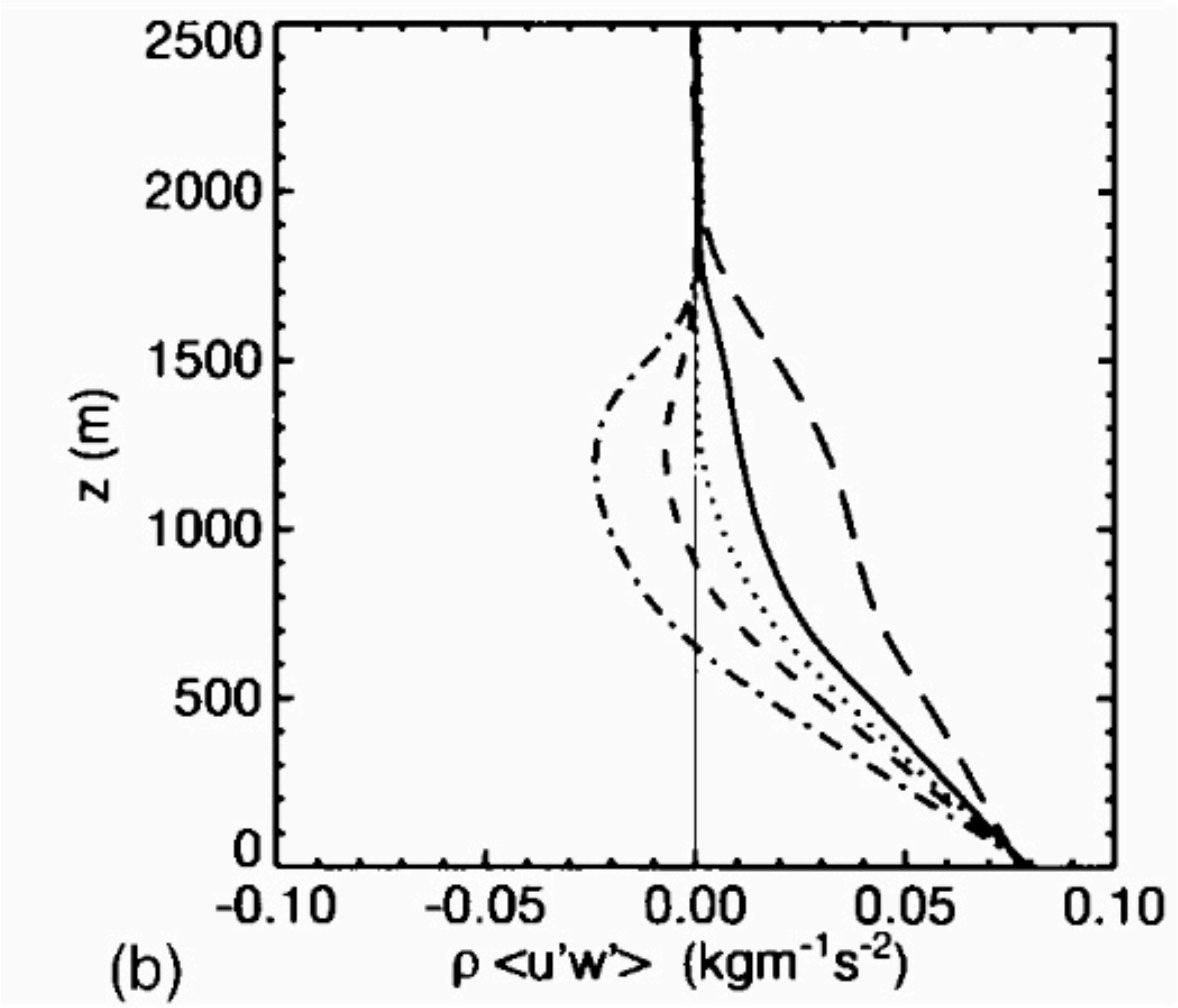
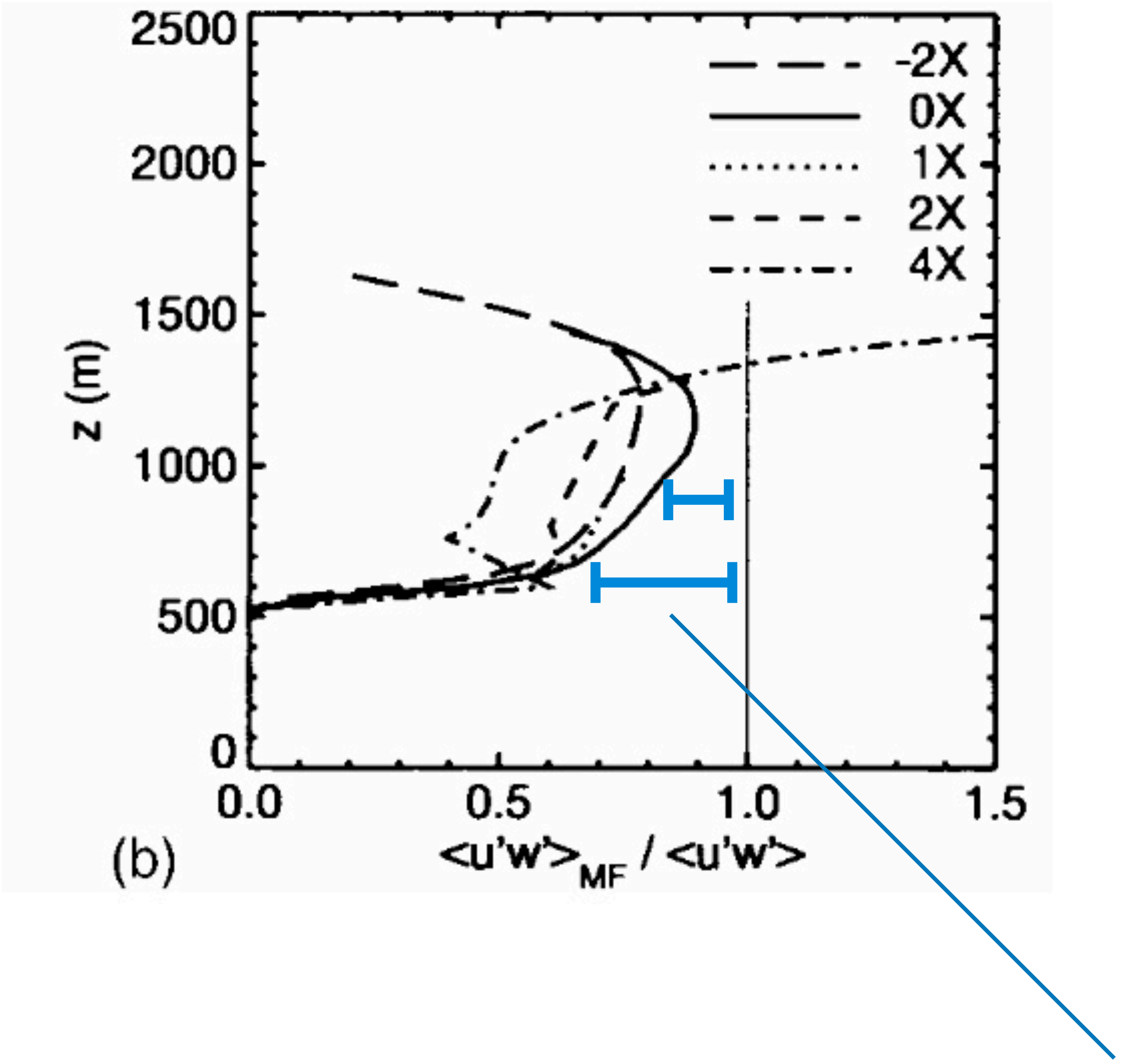
There is momentum to be gained at (sub)mesoscales

Mass flux does not suffice (environmental flux is significant) and pressure gradients matter for in-cloud momentum





Momentum flux not captured by mass flux

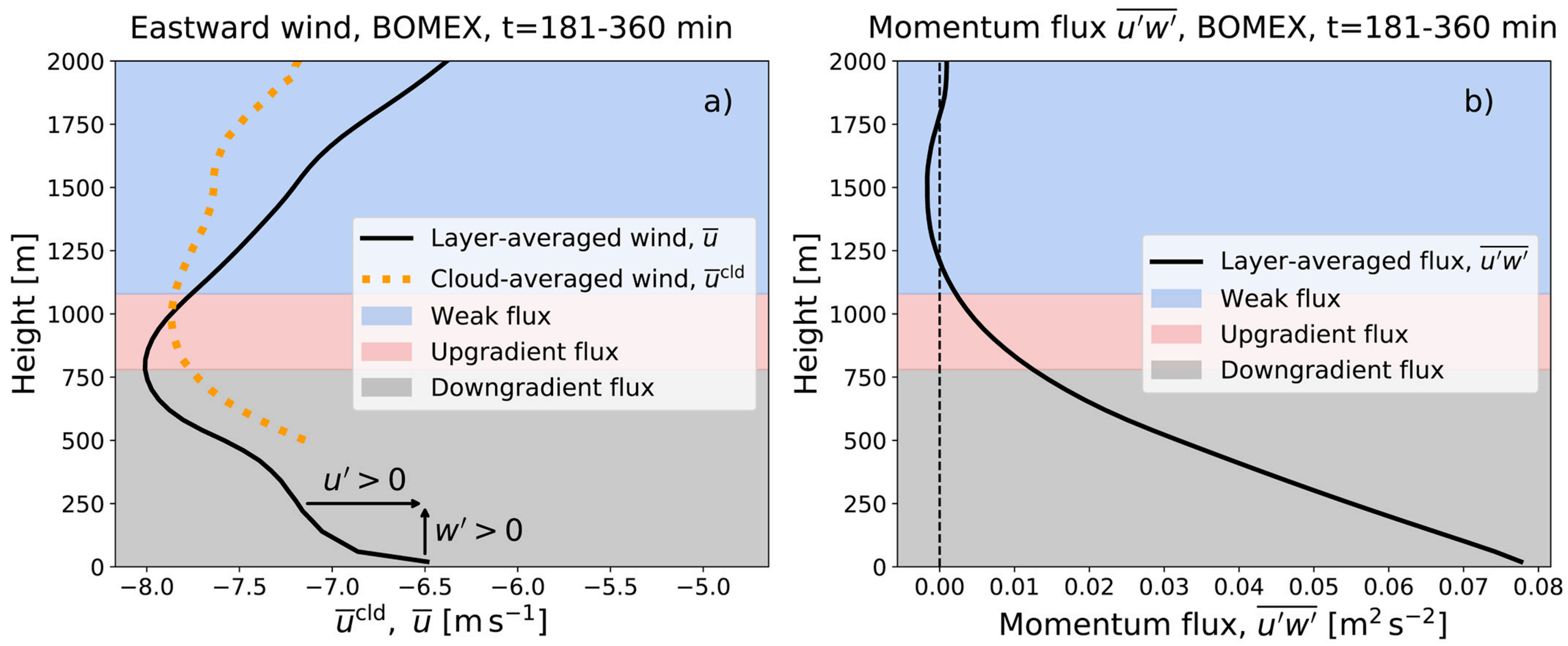
Brown (1999): BOMEX on 6.4 km x 6.4 km x 3.0 km, $\Delta x = 100$m

Zhu (2005): BOMEX/RICO on 16 × 16 km x 3 km, $\Delta x = 25$m

Schlemmer et al (2017): RICO on 51.2 km × 51.2 km × 5 km, $\Delta x = 25$m

Larson et al (2019): RICO on 51.2 km × 51.2 km × 5 km, $\Delta x = 100$m

A layer of upgradient momentum flux is created by non-local transport through a zonal wind jet



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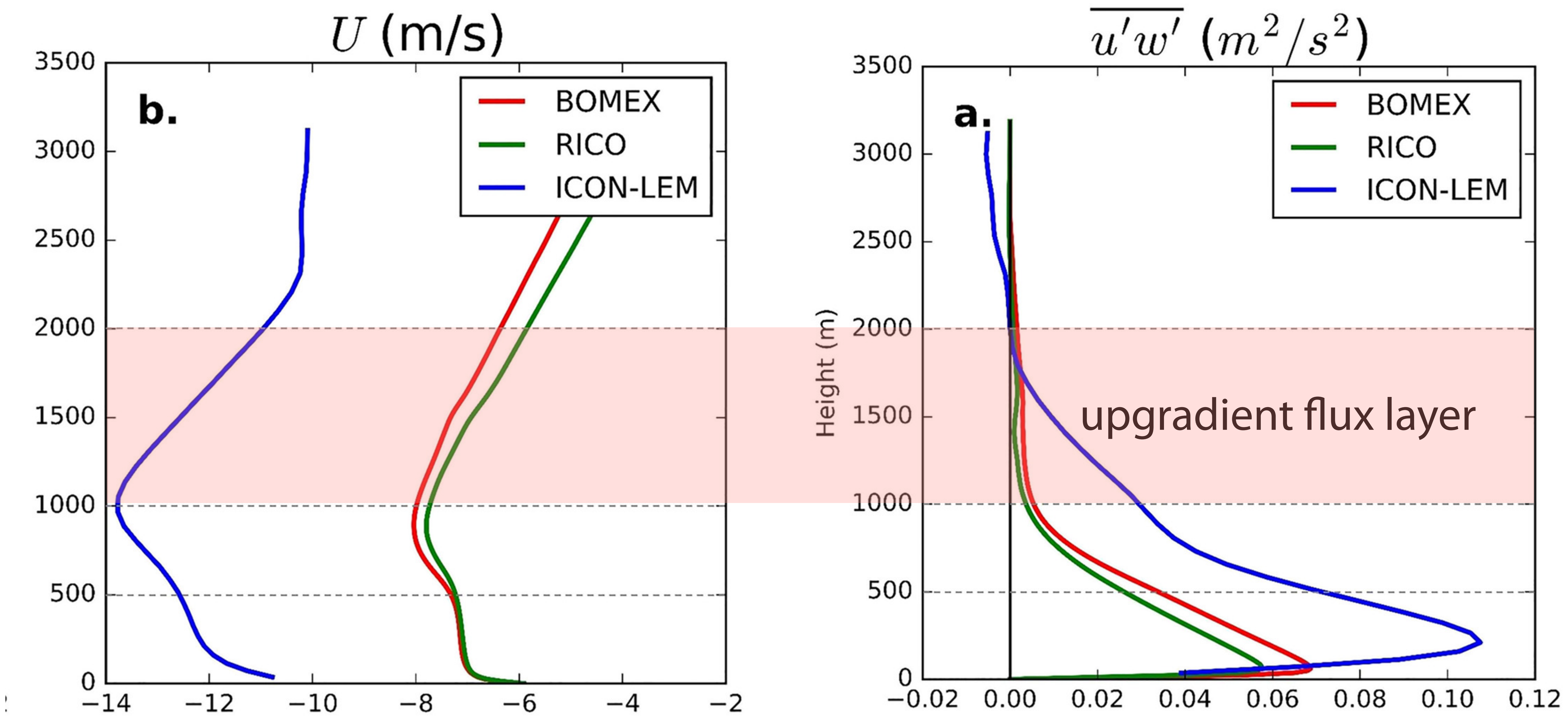
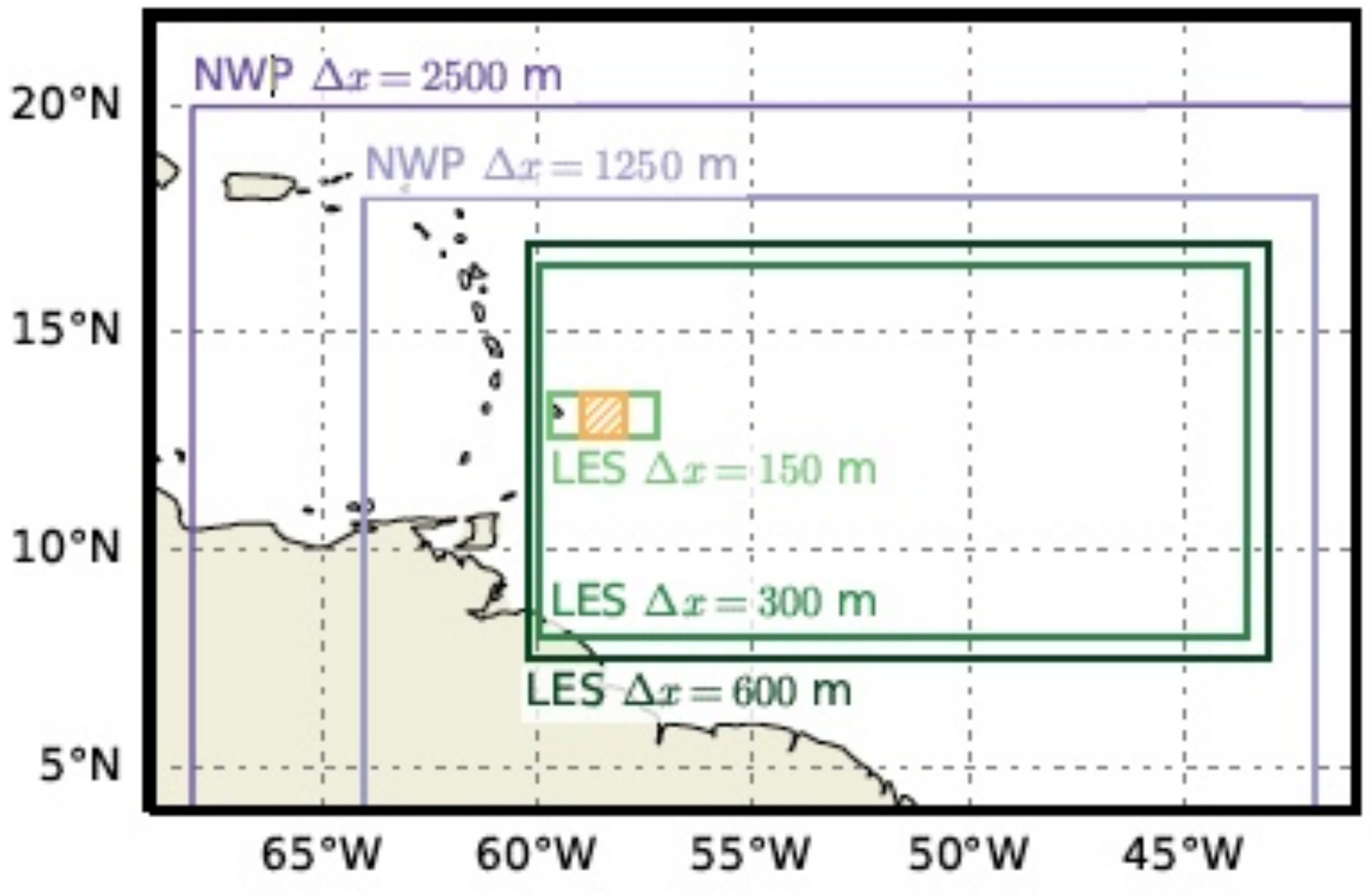
Deeper layer of upgradient flux in open-boundary ICON-LEM hindcasts

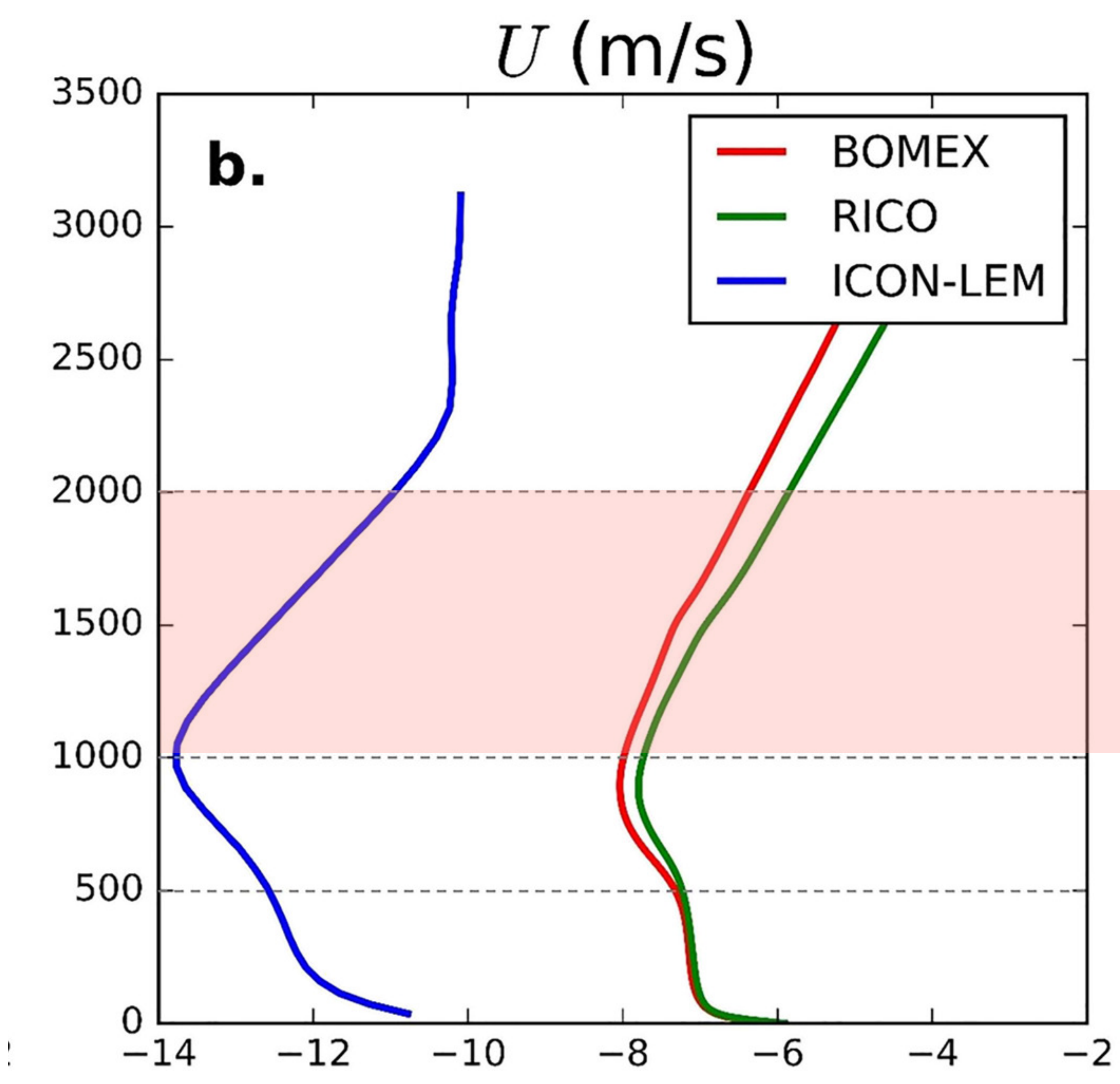


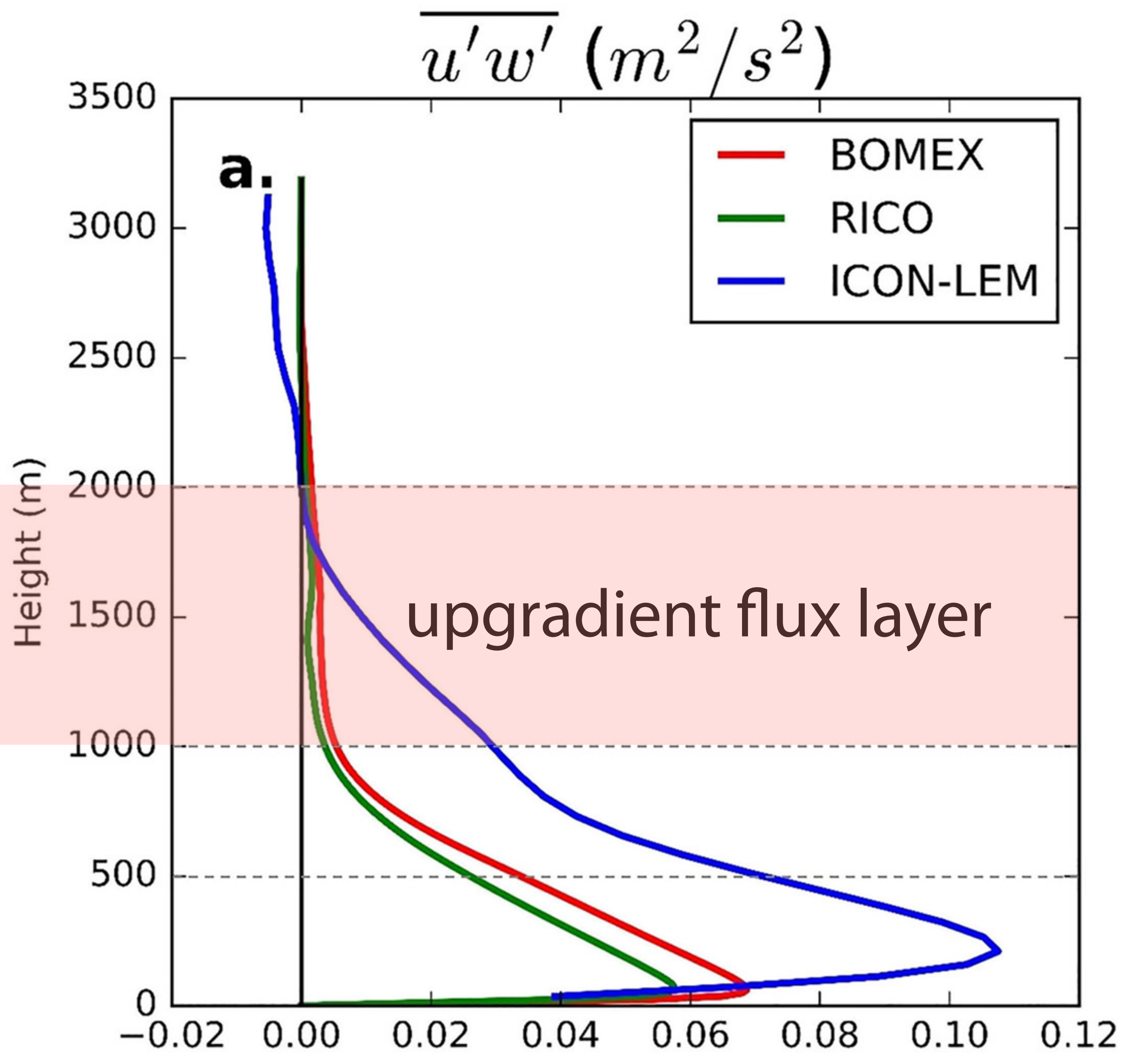


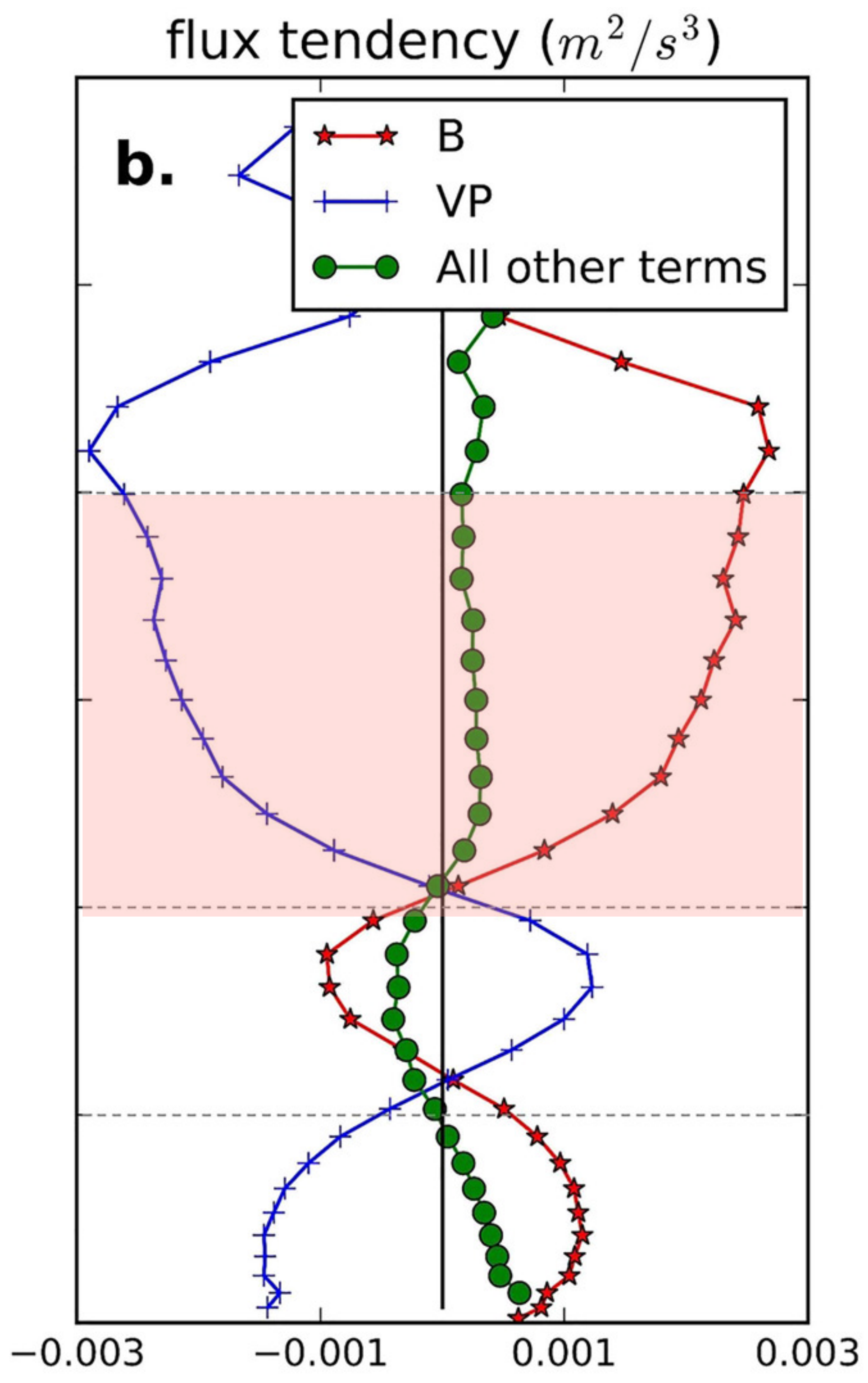
Dixit et al (2020): NARVAL with ICON-LEM on 100 km x 100 km x > 5 km, Δx = 150 m

Simulations by Matthias Brueck and Daniel Klocke

Buoyancy generation of flux largely compensated by vertical pressure perturbations





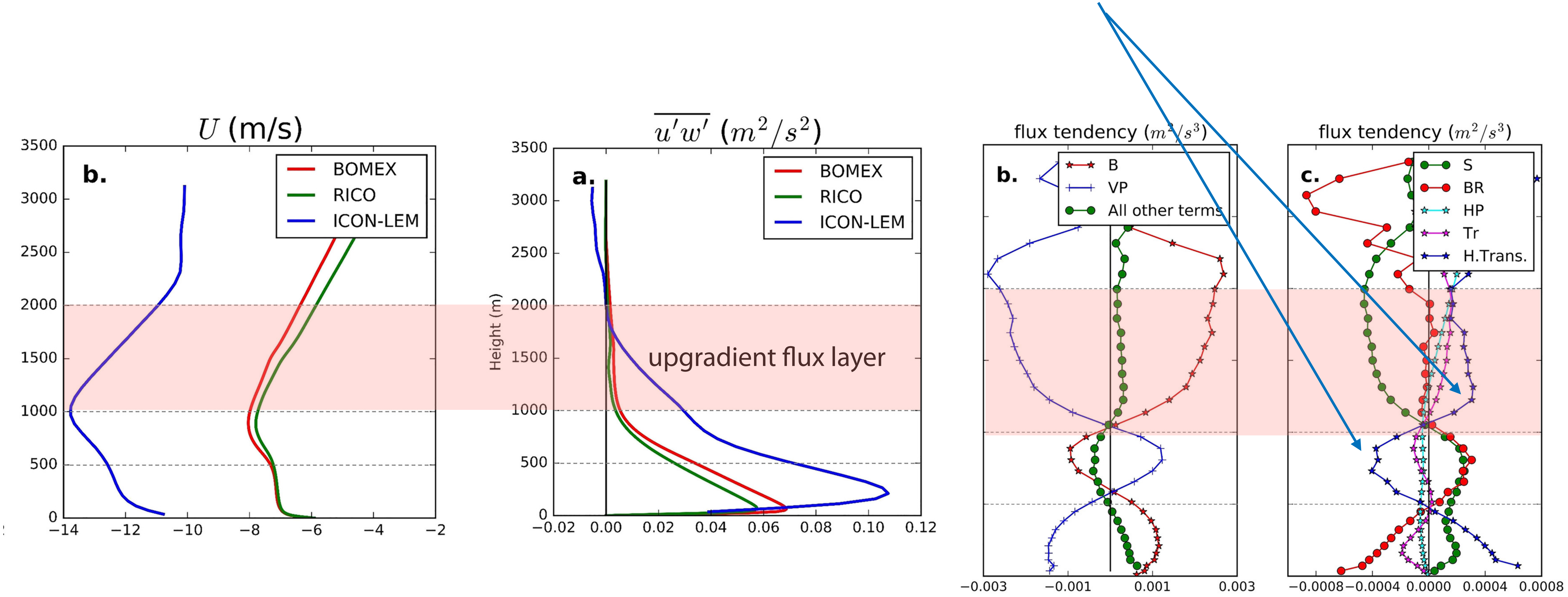


$$BR = \frac{g}{\overline{T_v}}\overline{u'T_v'} - \overline{\frac{u'}{\overline{\rho}}\frac{\partial p'}{\partial z}}$$

Buoyancy **V**ertical **P**ressure Gradient

Dixit et al (2020): NARVAL with ICON-LEM on 100 km x 100 km x > 5 km, Δx = 150 m

Upgradient flux generated by horizontal convergence of flux by wind (perturbations)



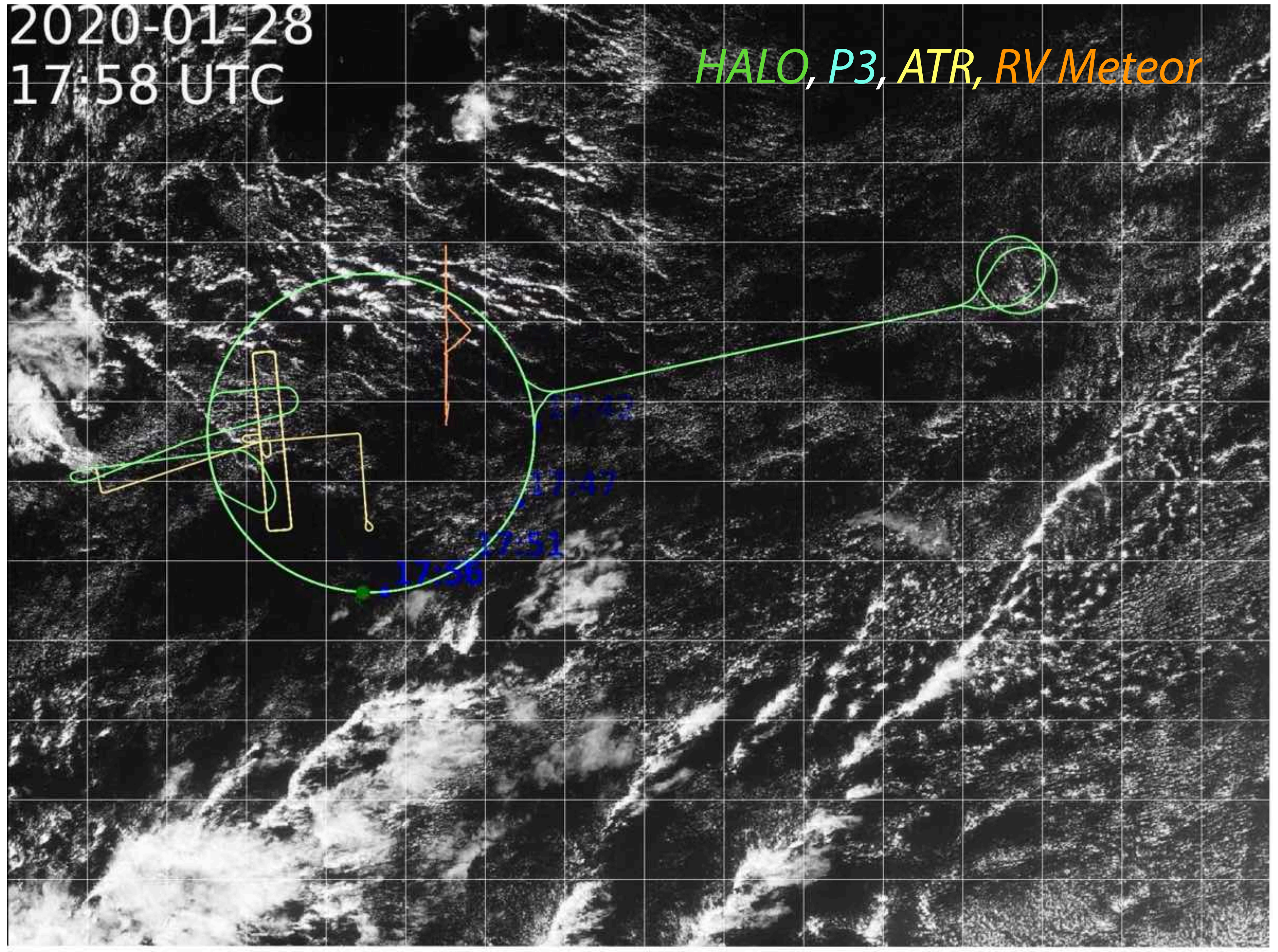
Buoyancy residue
Shear
Horizontal Pressure Grad
Vertical transport
Horizontal transport

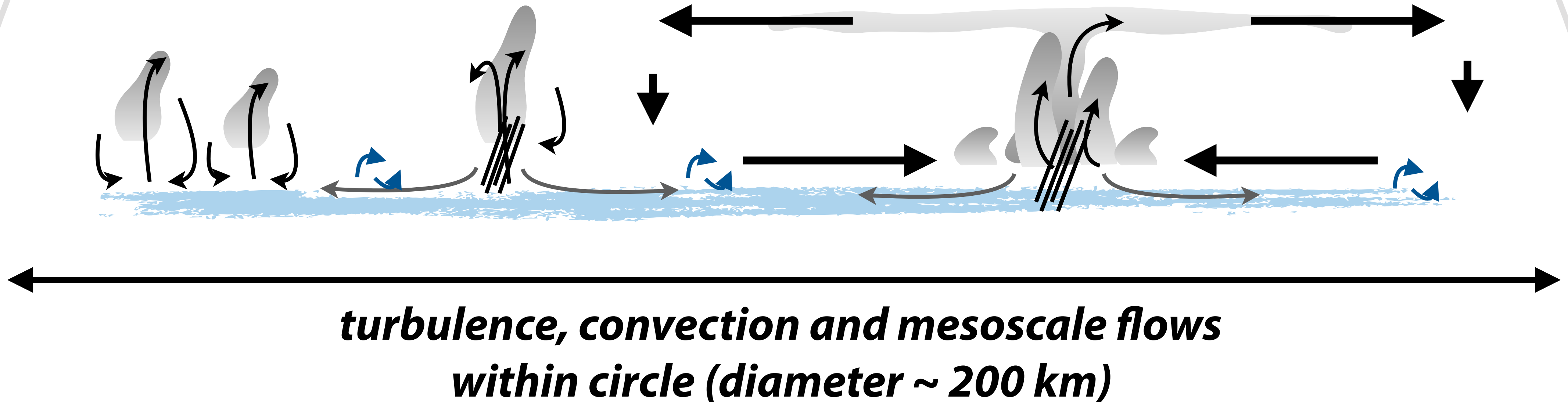
Dixit et al (2020): NARVAL with ICON-LEM on 100 km x 100 km x > 5 km, Δx = 150 m

EUREC4A 's rich data set and hierarchy of model simulations are used to explore momentum transport by different flows

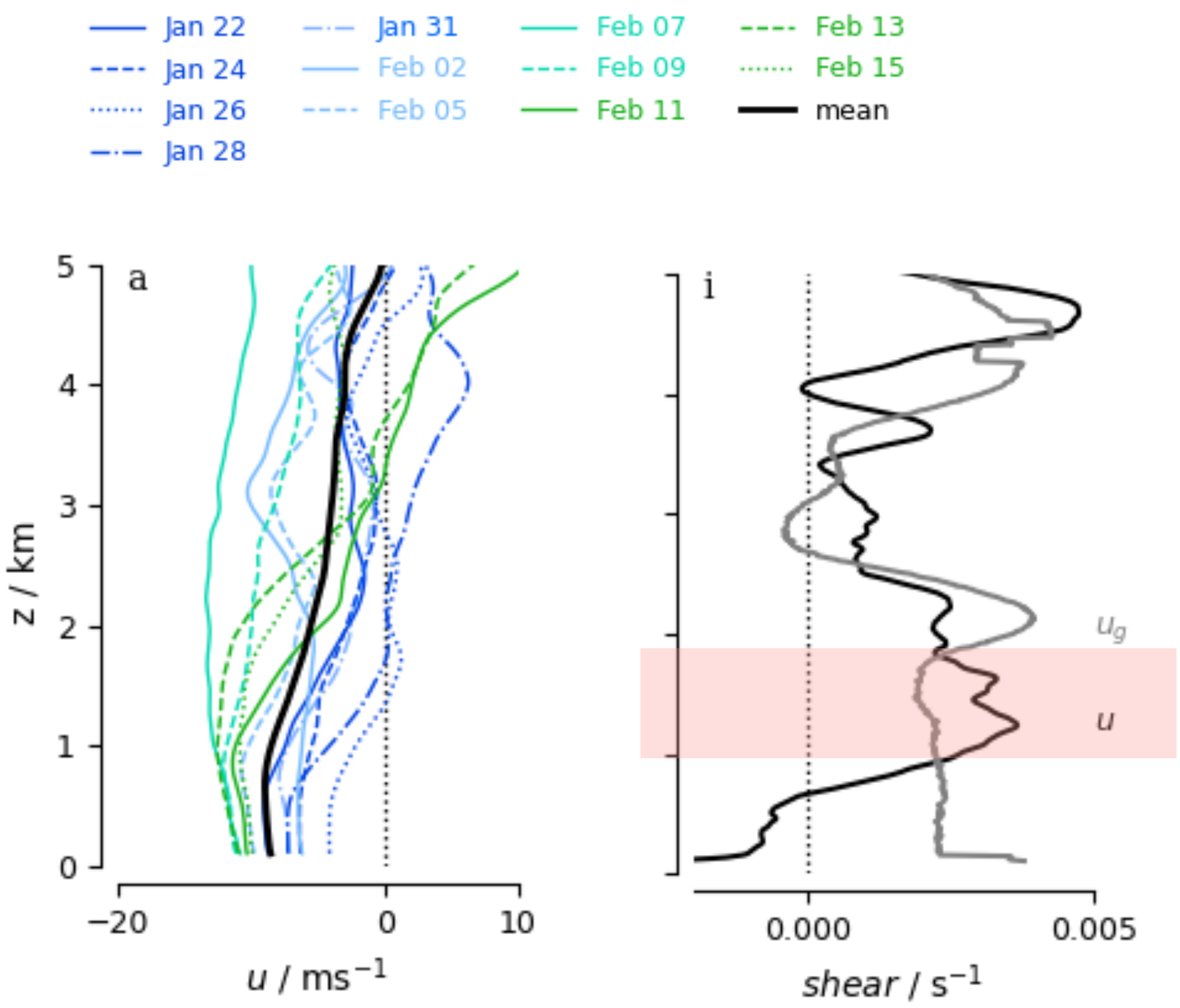
* **JOANNE: circular dropsonde arrays** (85 circles, 13 flight days): meso-scale divergence, pressure gradients and geowind

* **French ATR Safire aircraft / UAVs:** profiles of in-situ turbulence





Supportive evidence of upgradient momentum transport and heterogeneity in flux along flight tracks, including near cloud tops



actual wind shear > shear in geo-wind

Nuijens et al (2022, in print for QJRMS)

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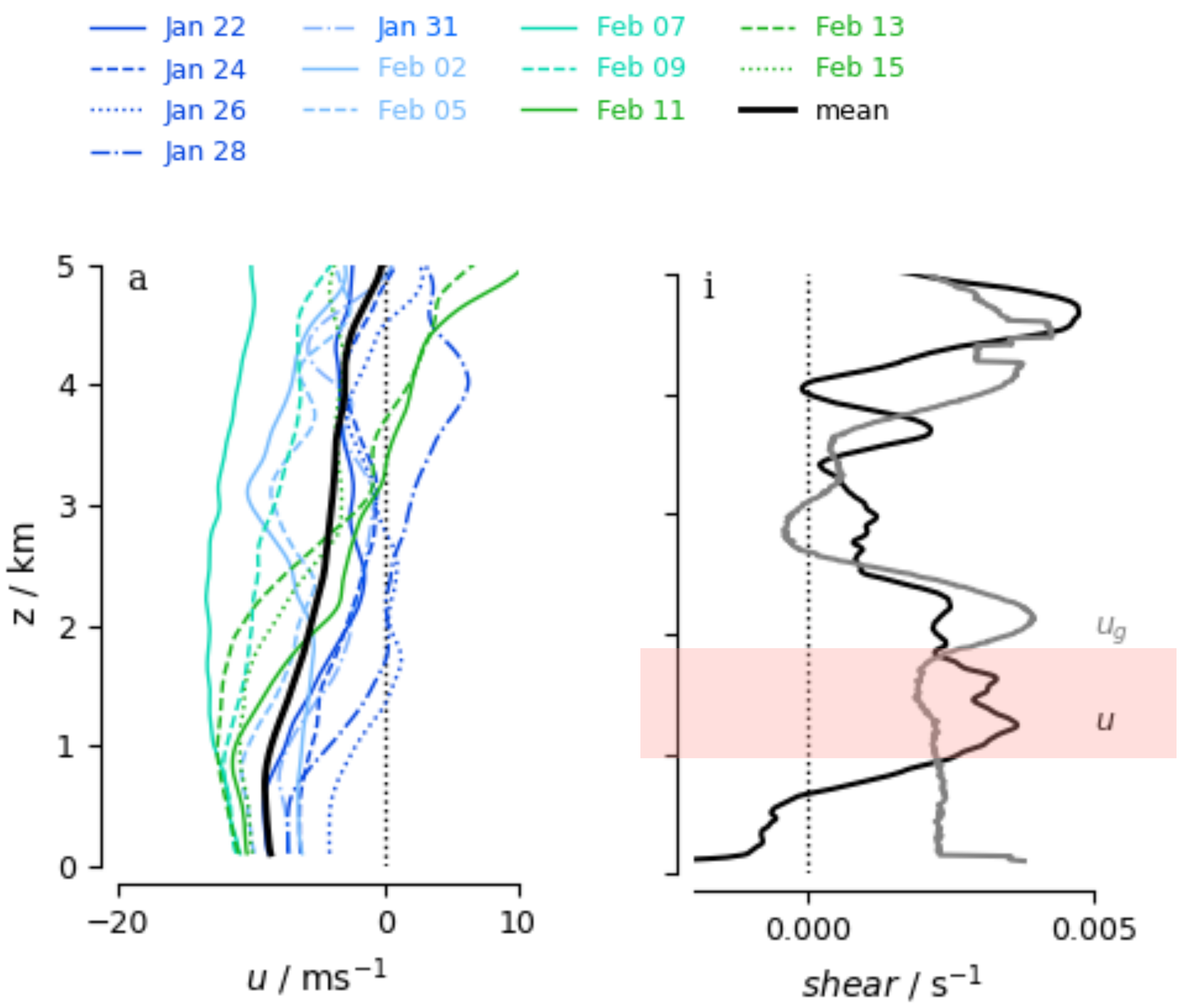

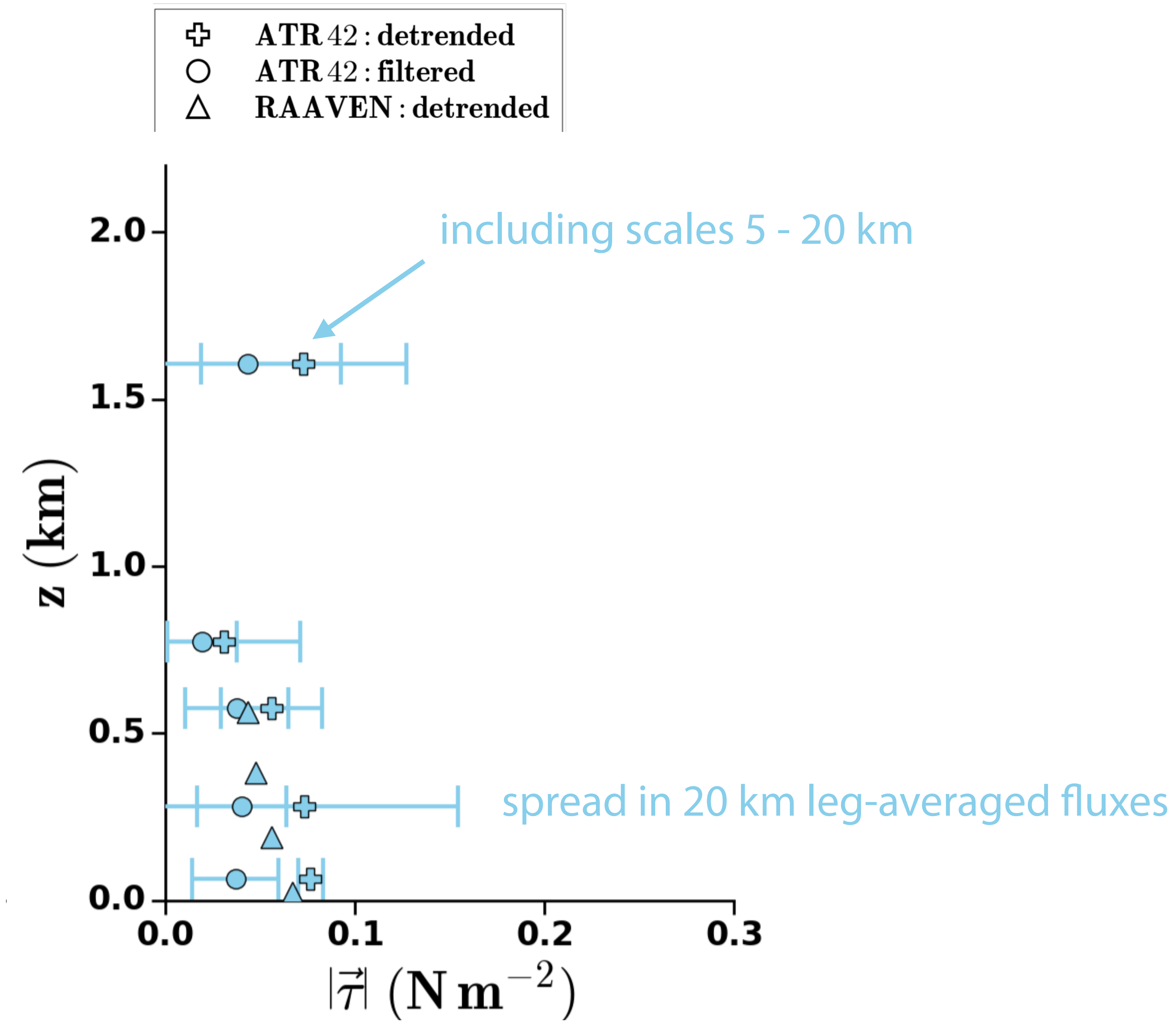

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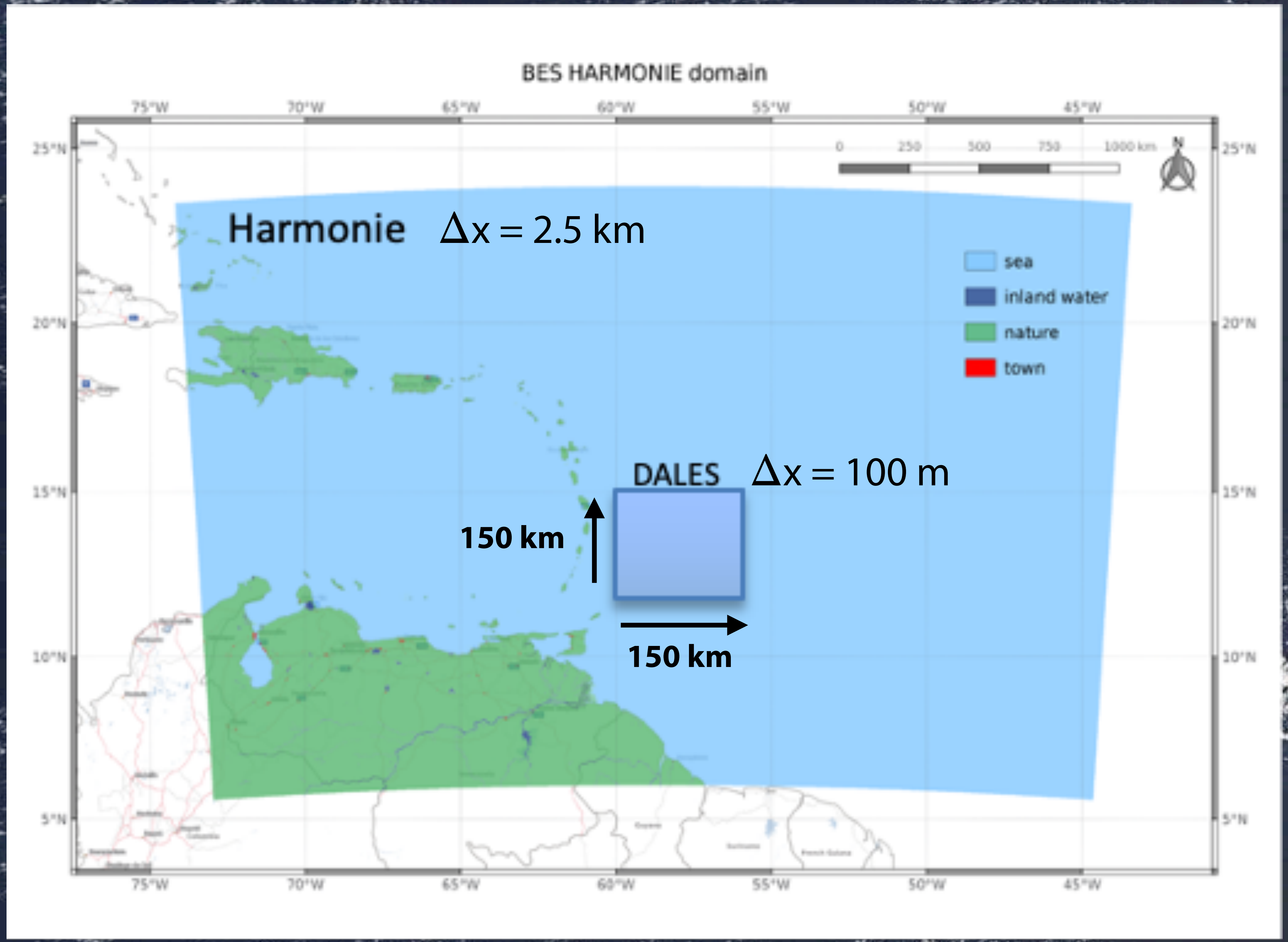
LEM and SRM hindcasts/climatological simulations of a ten-day EUREC4A period



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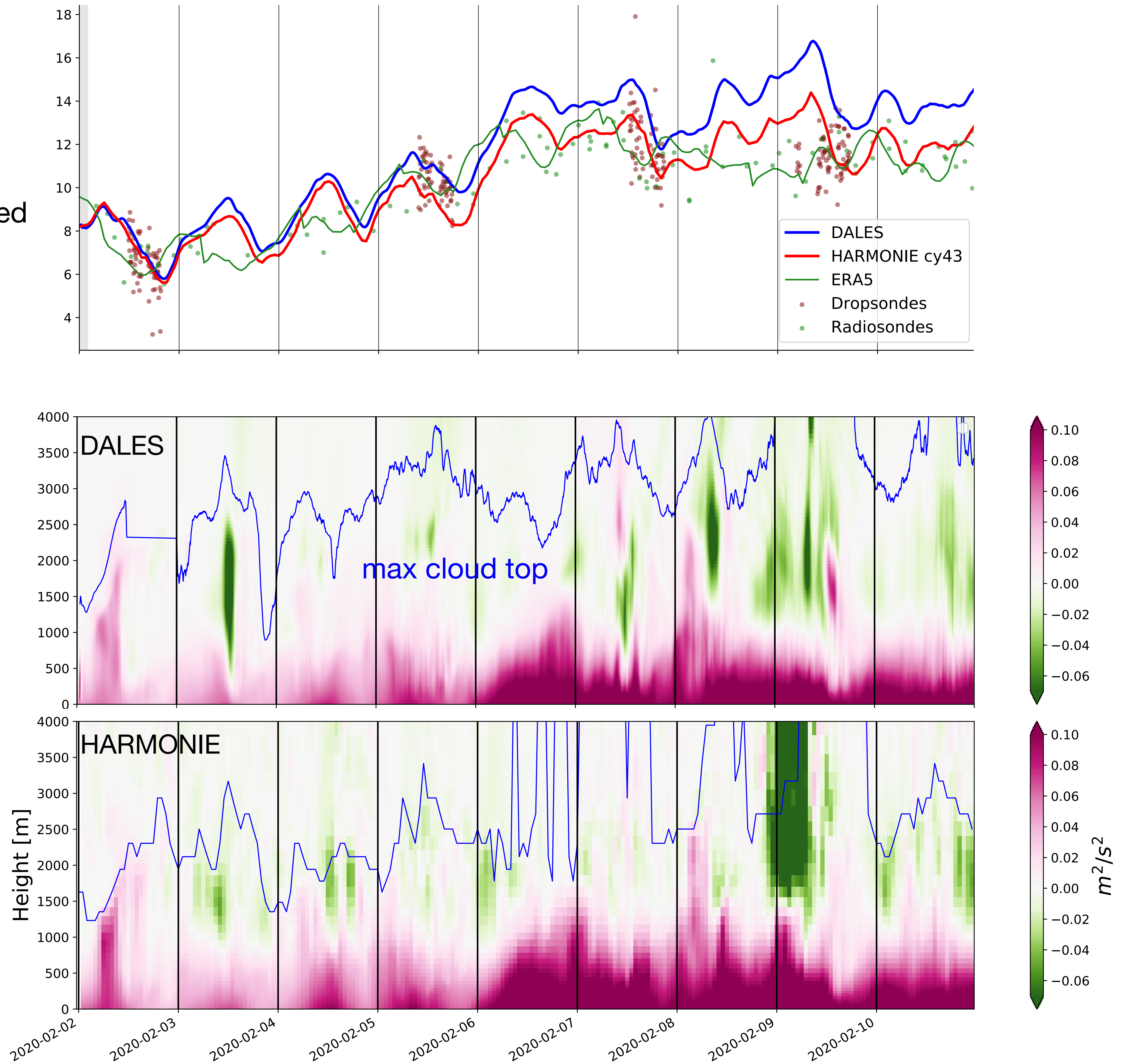
As trade-winds strengthen, convection drives strong (upgradient) momentum flux

wind speed (300 m)



zonal momentum flux

Figures by: Alessandro Savazzi

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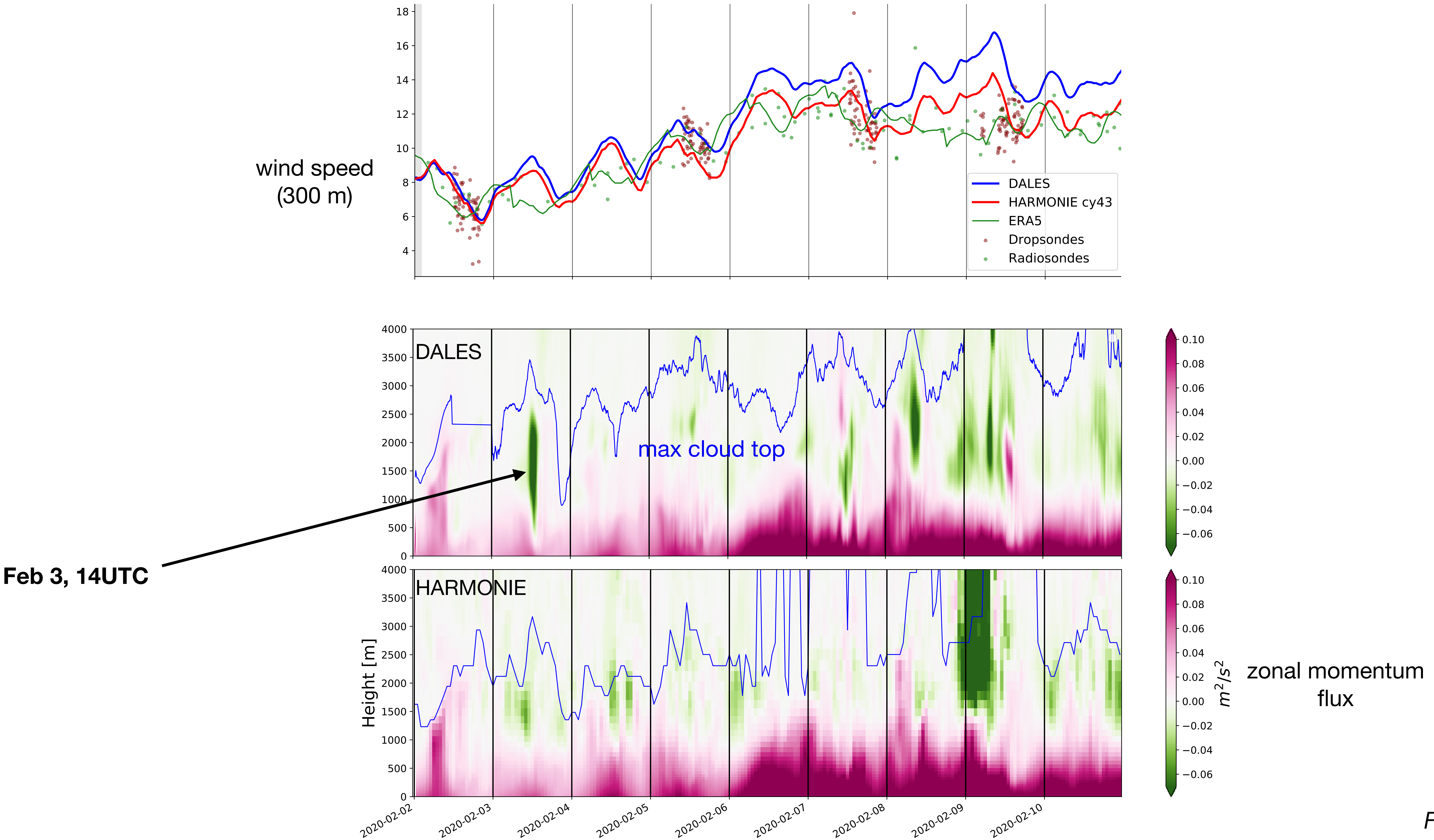
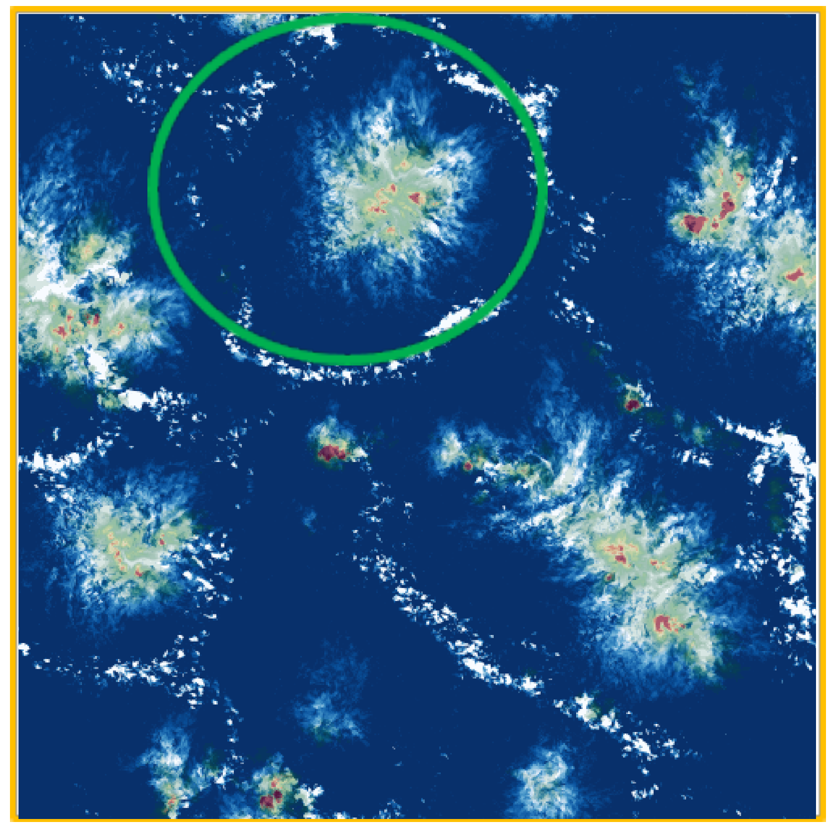


Figures by: Alessandro Savazzi

Large anomalies in wind speed in surface layer and near cloud tops



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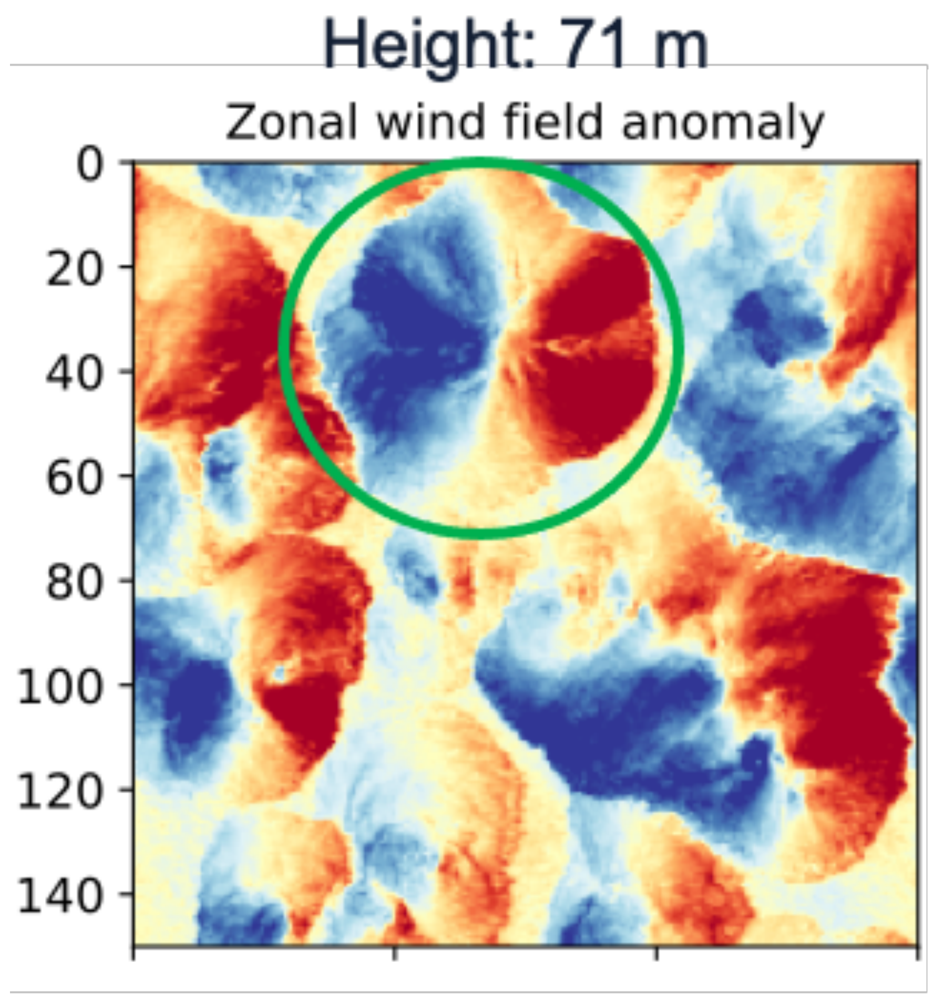

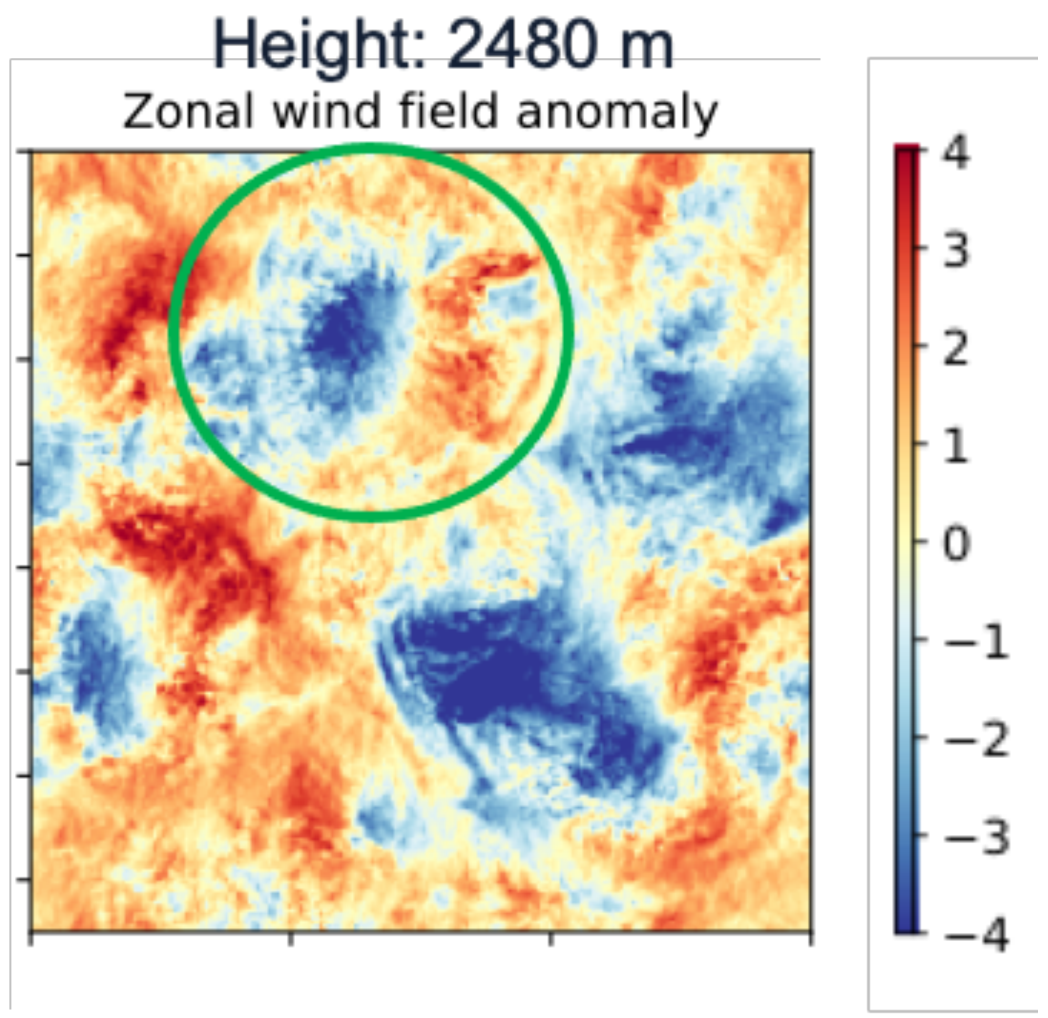

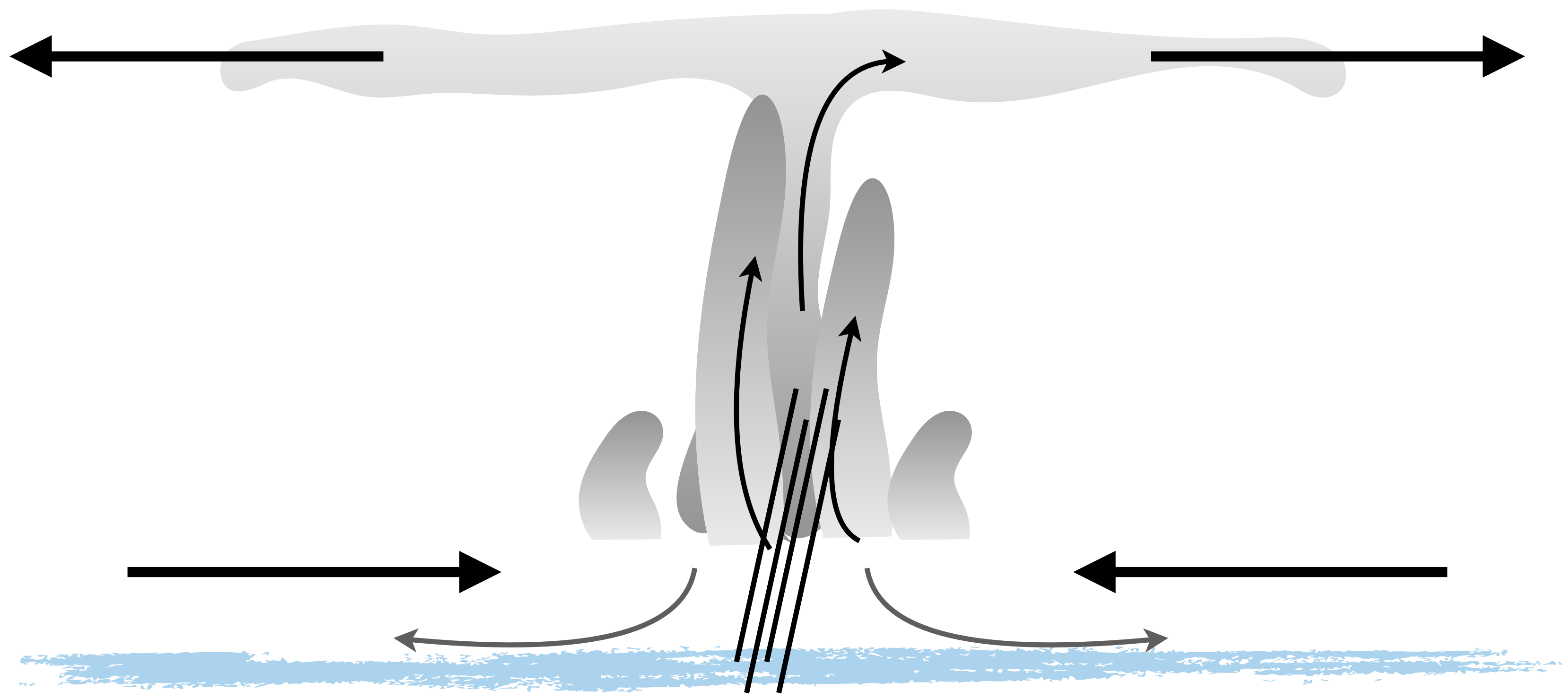

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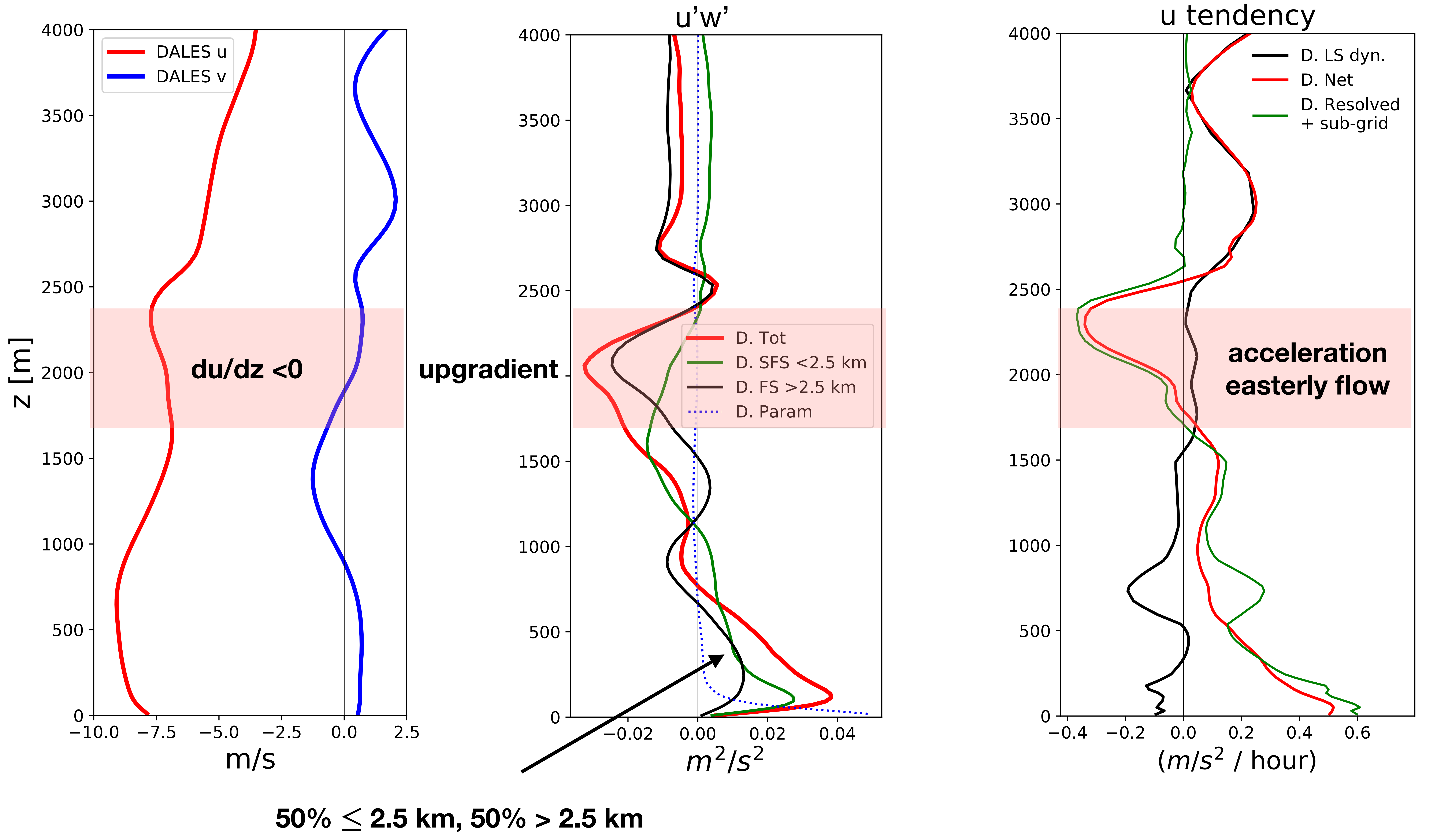
Mesoscale flows important for upgradient transport and acceleration near cloud tops, but also for generating flux in the mixed-layer



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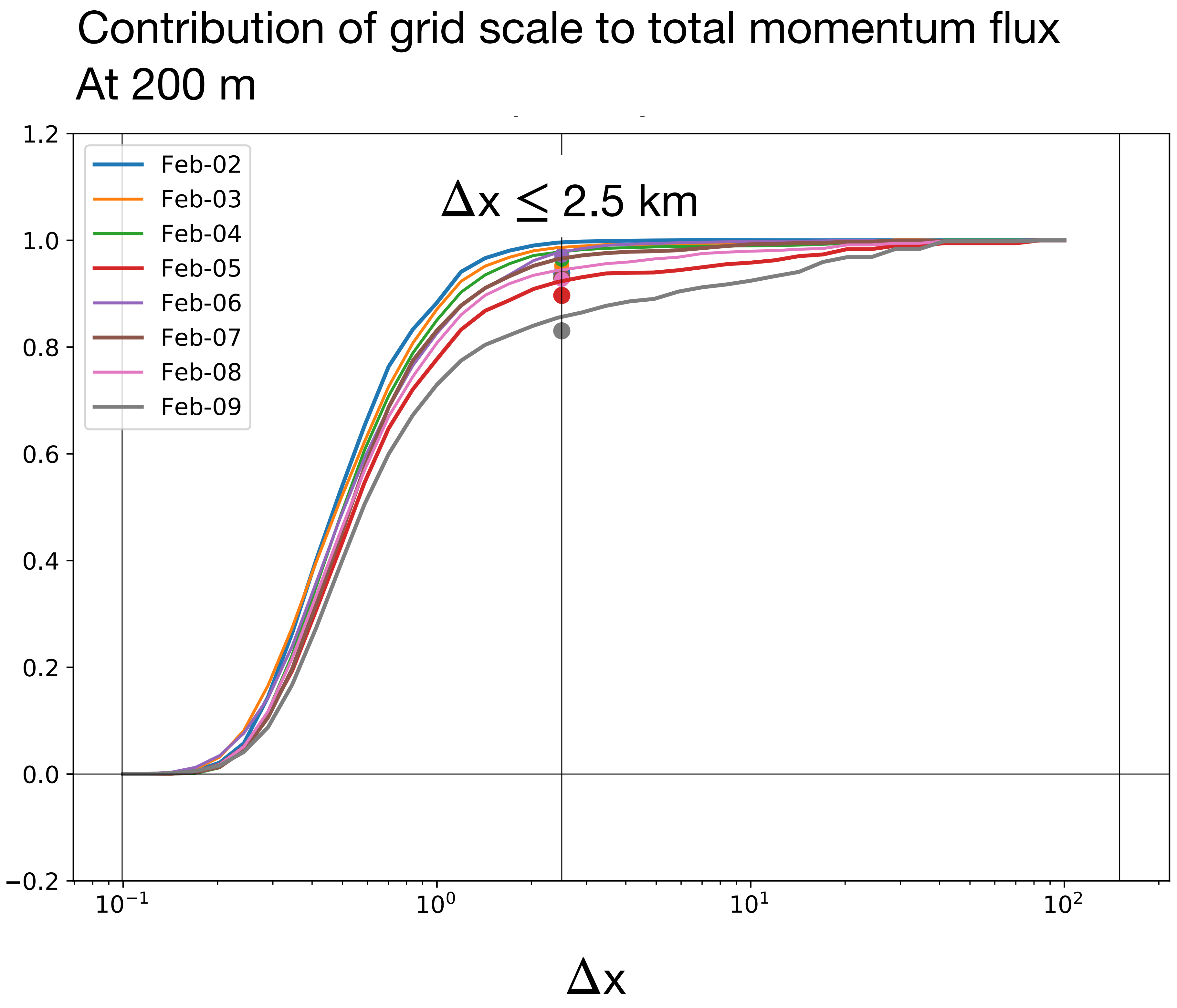
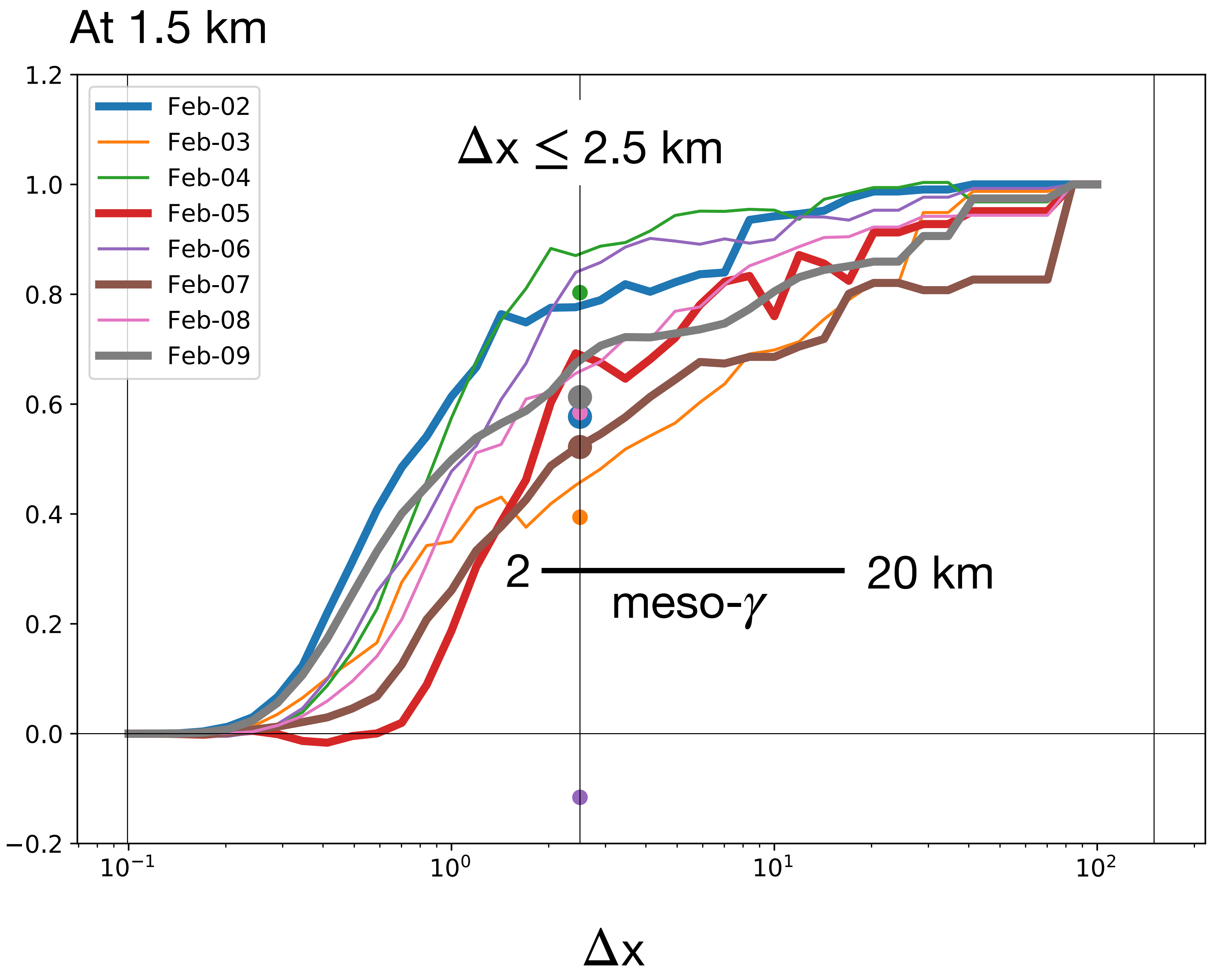
(Sub)mesoscales can contribute up to 50% of the momentum flux in the cloud layer





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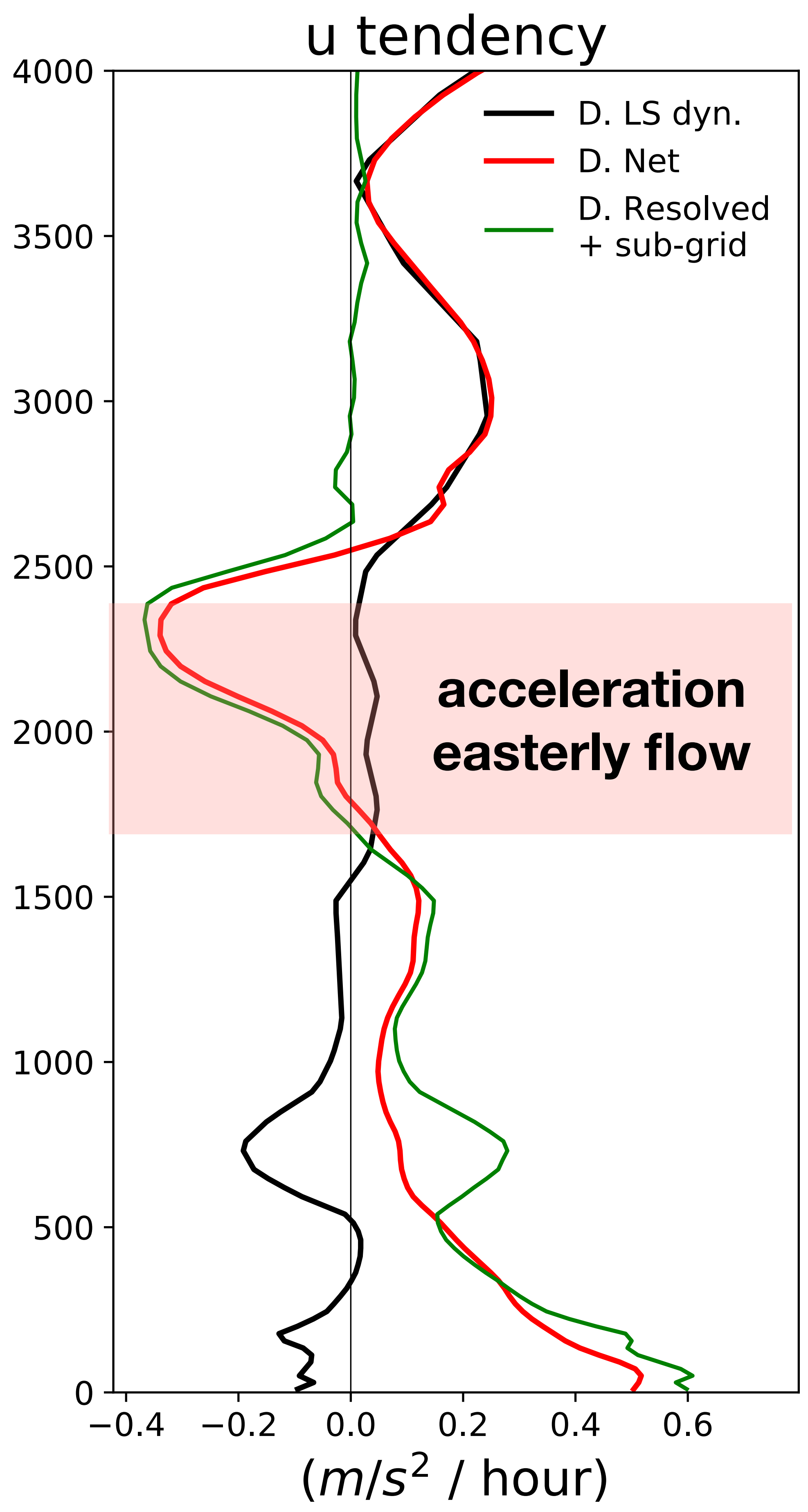
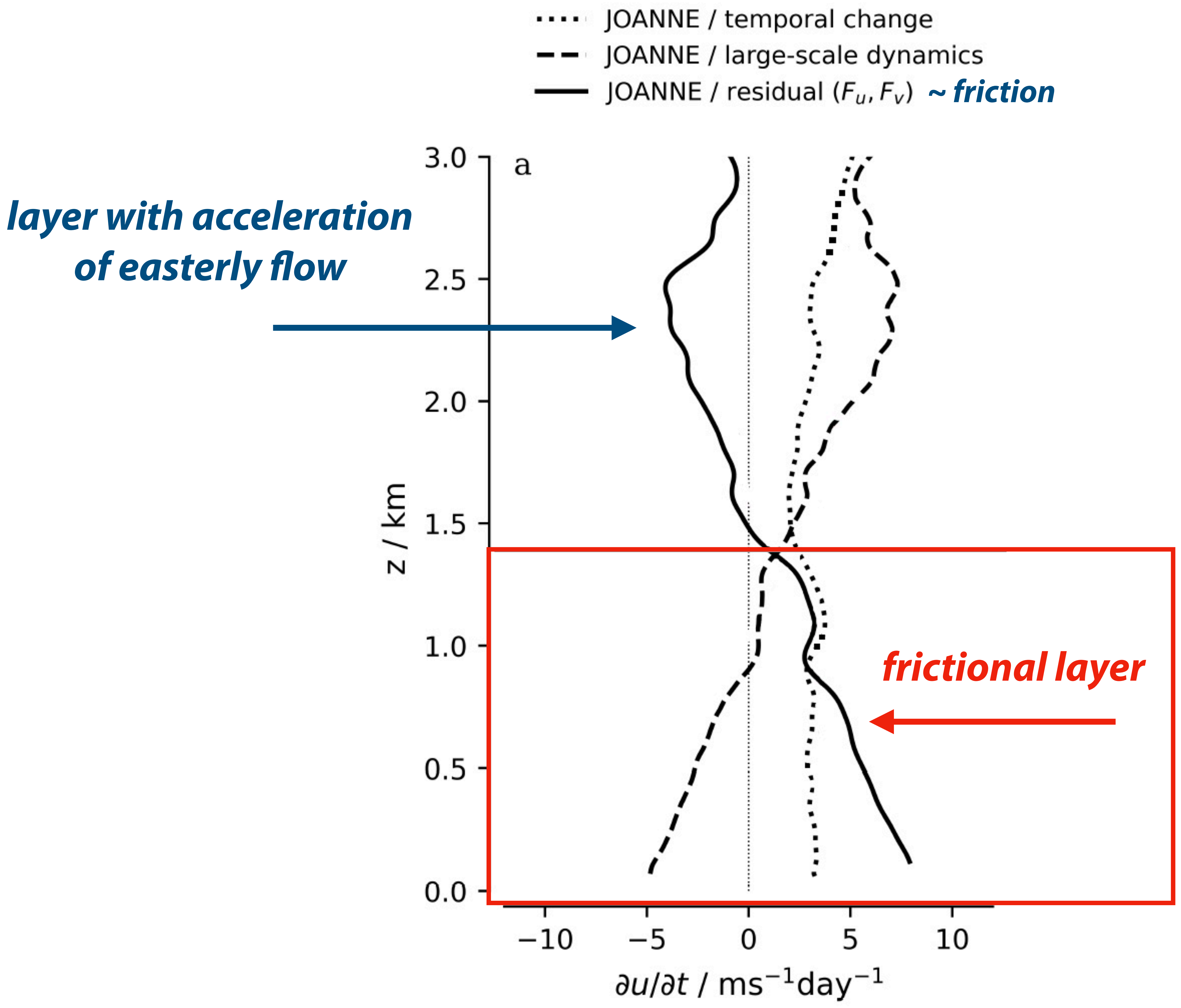
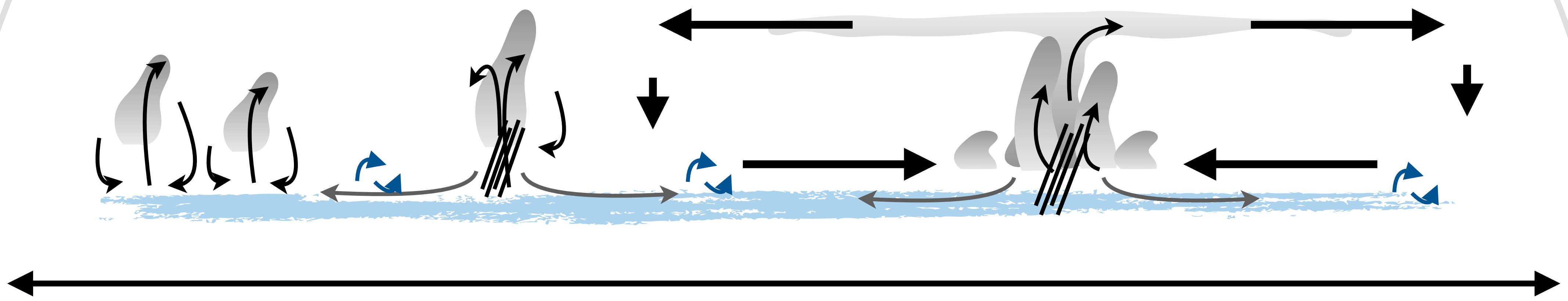
Link to bias in zonal winds?



Savazzi, Nuijens, Sandu, George and Bechtold (ACP, accepted)

Convective, mesoscale flows create a deeper layer of easterly flow





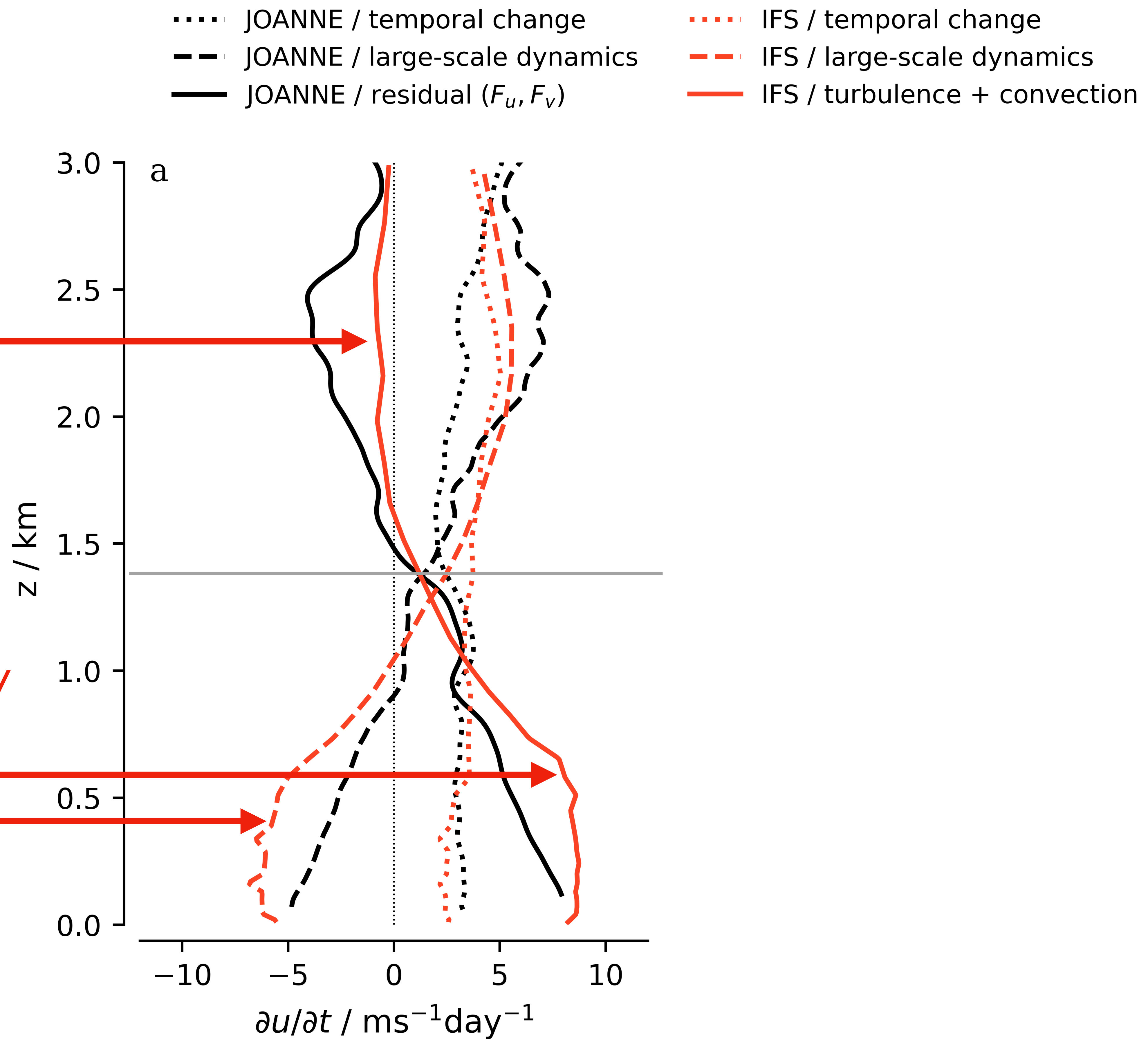
turbulence, convection and mesoscale flows within circle (diameter ~ 200 km)

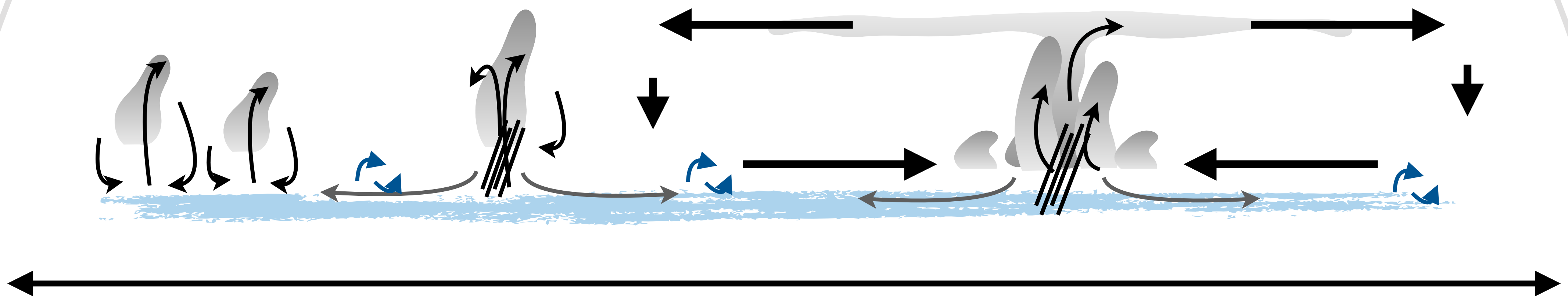
Savazzi, Nuijens, Sandu, George and Bechtold (ACP, accepted)

Does organised convection help explain the weak zonal wind bias ?

missing convective tendency in IFS above 1.5 km

compensating physics/ dynamics errors





turbulence, convection and mesoscale flows within circle (diameter ~ 200 km)

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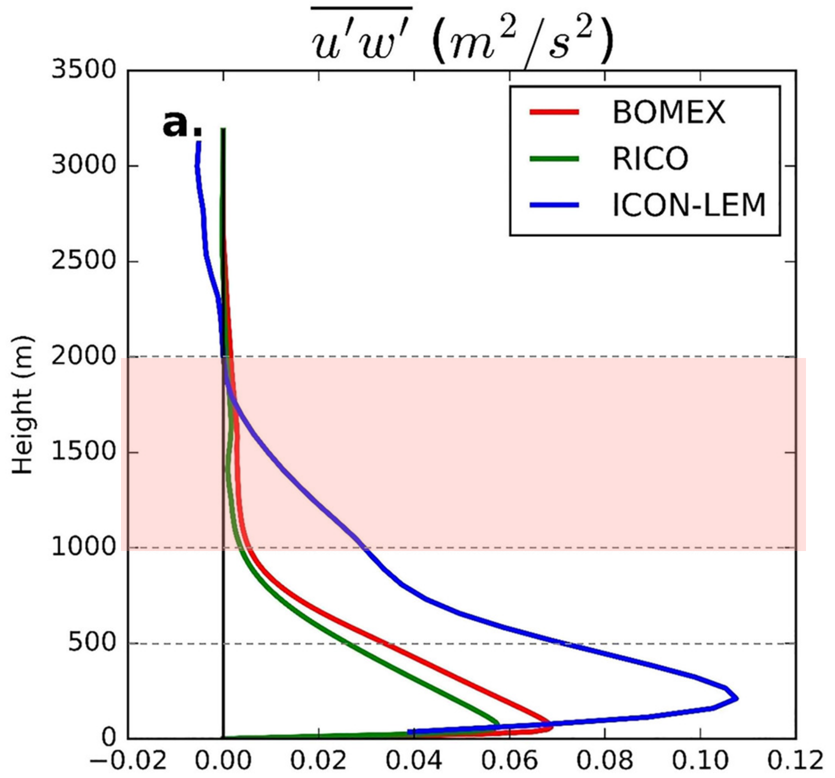
Summary

- In larger domain LEM with open boundary conditions and varying large-scale tendencies, horizontal transport and generation of momentum flux gains importance: more upgradient transport than perhaps appreciated



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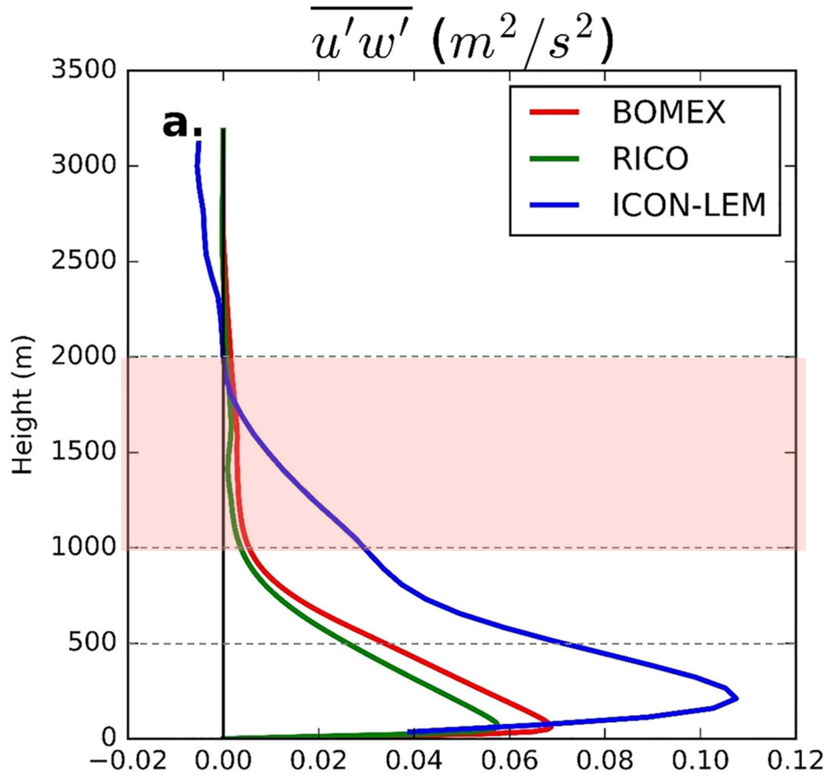

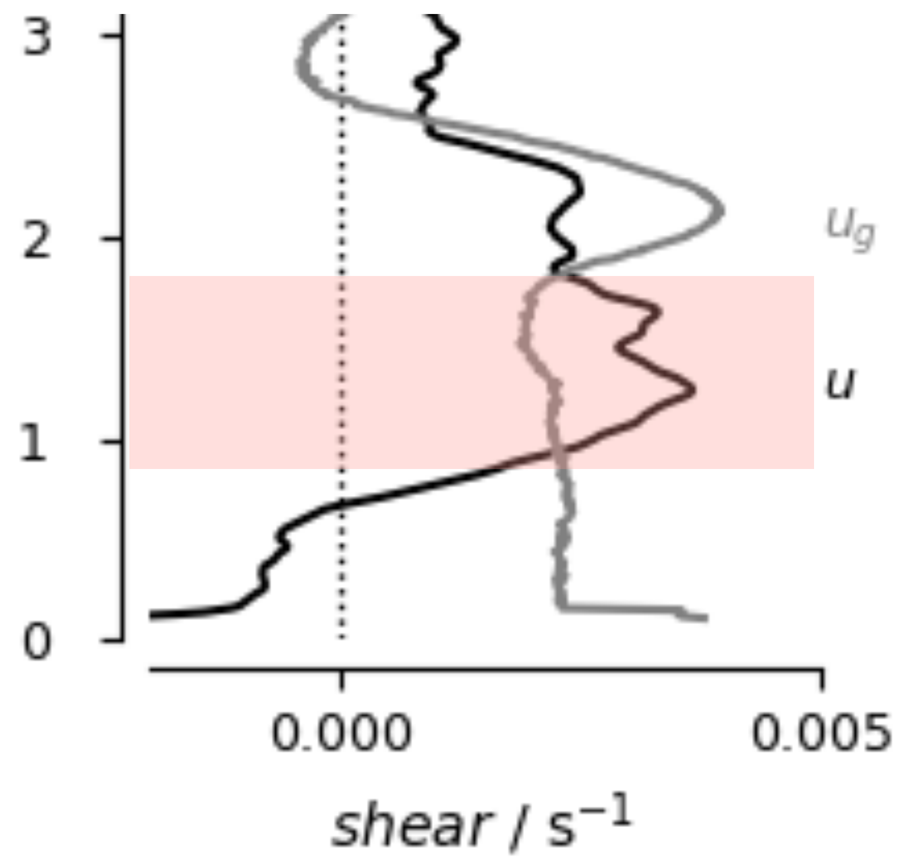

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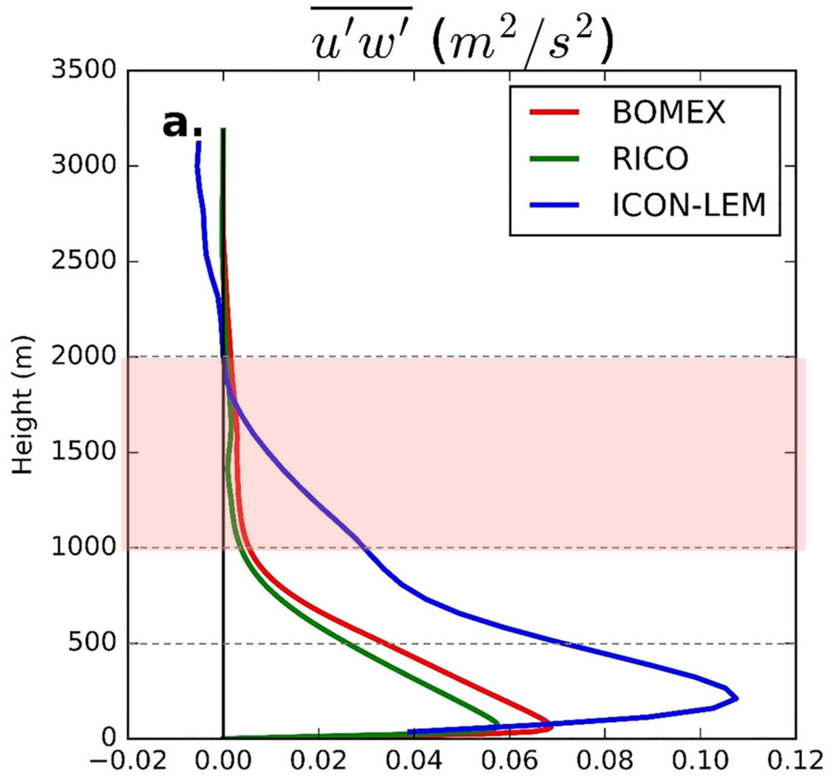
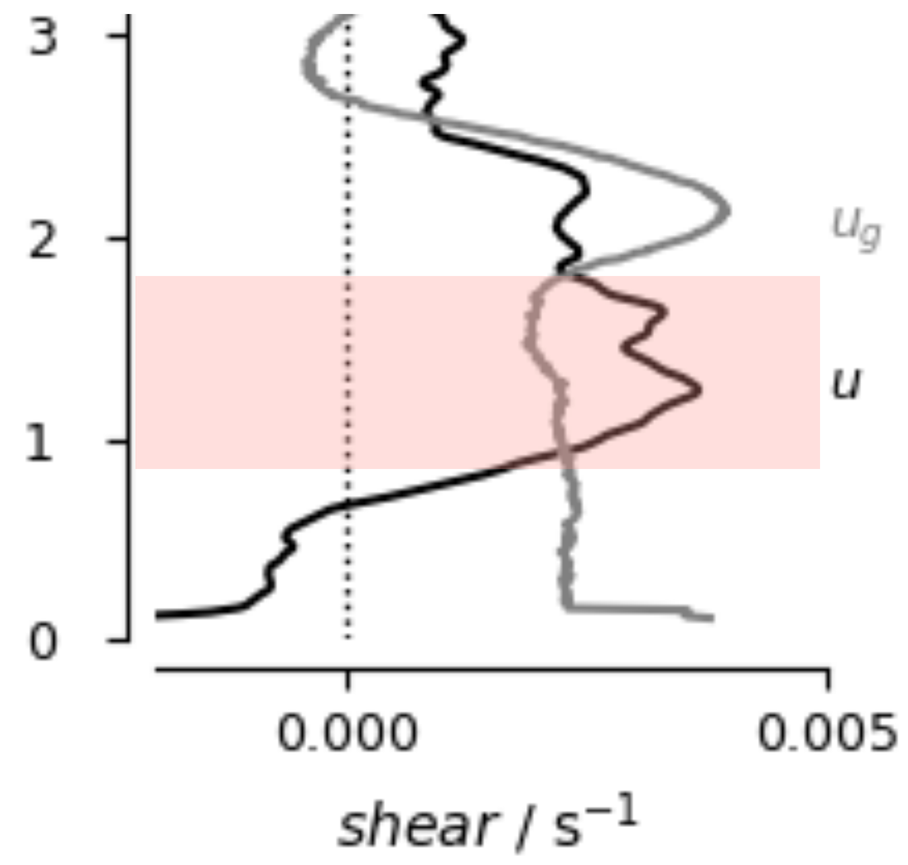
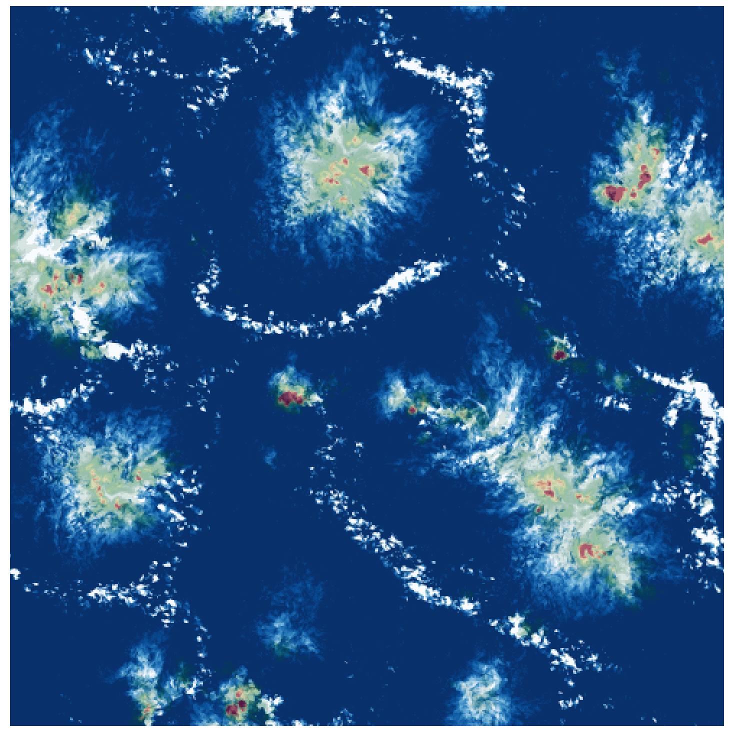
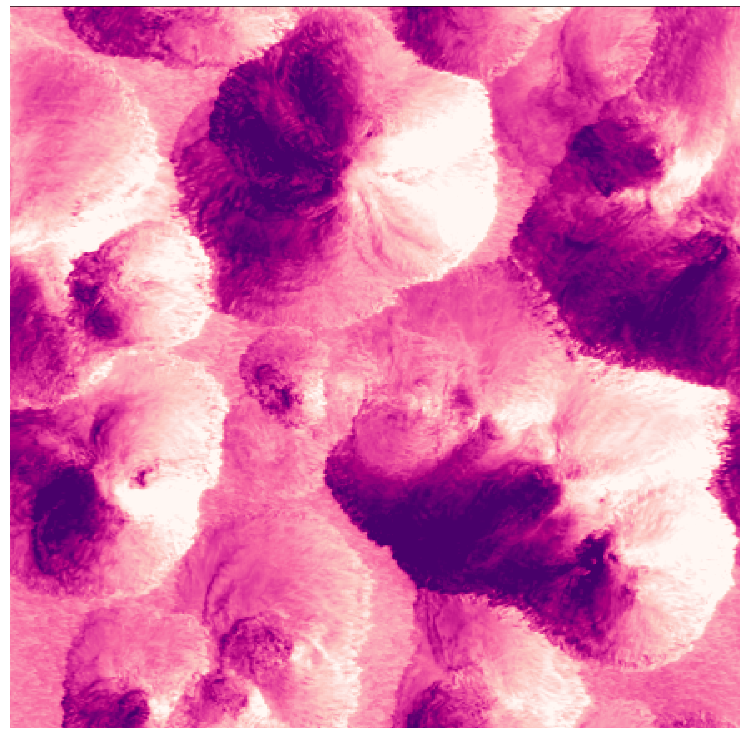
- At times of vigorous shallow convection (gravel, flowers - congestus) up to half the momentum flux is carried by scales > 2.5 km (in the cloud layer, but also the sub-cloud layer)

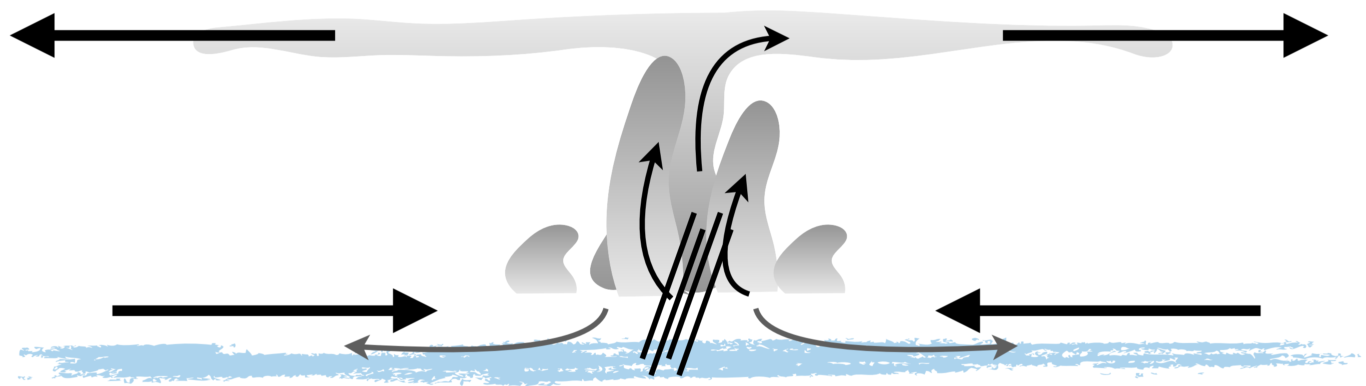
- Convection accelerates winds near the surface, but also near cloud tops.





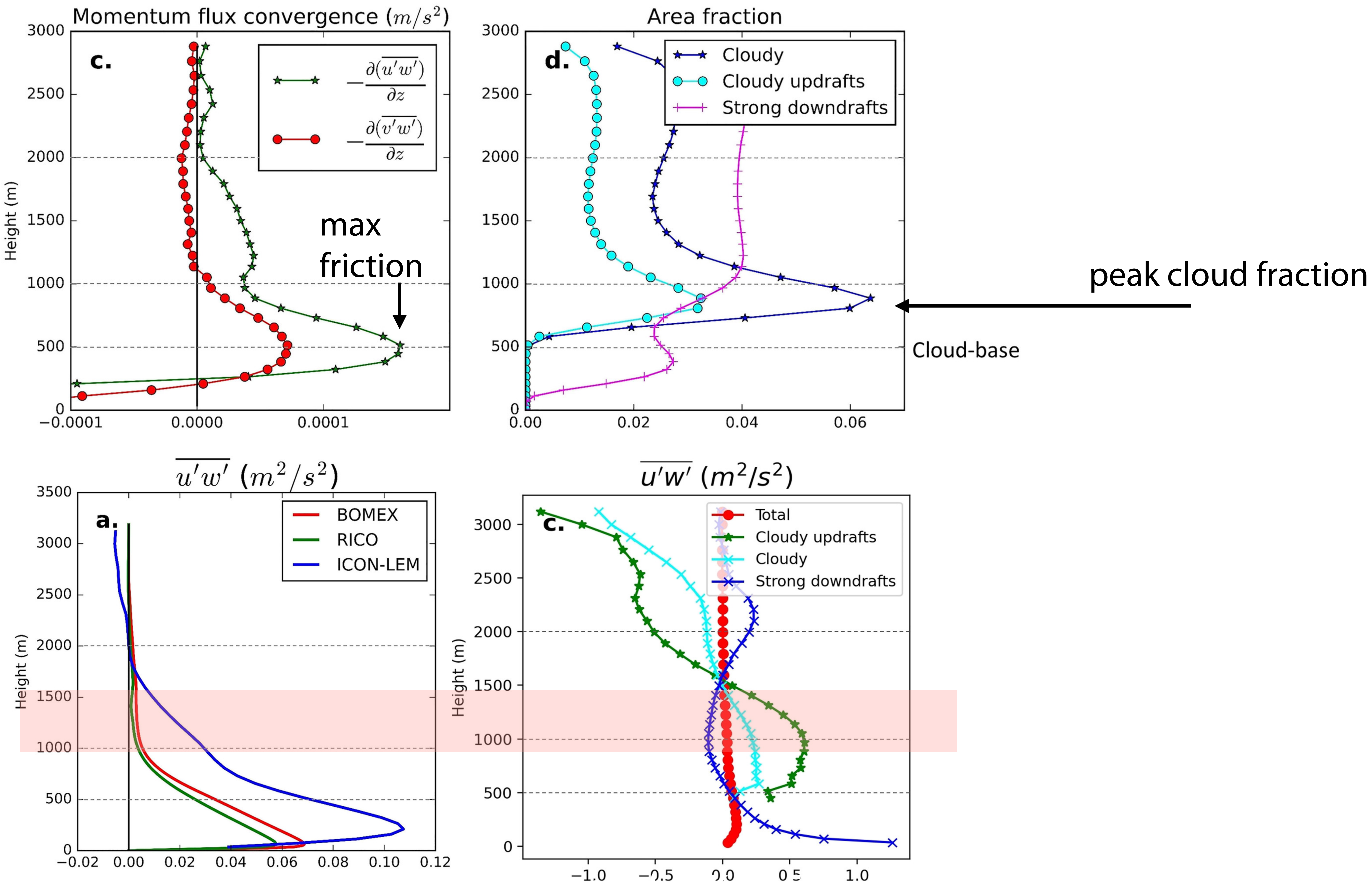


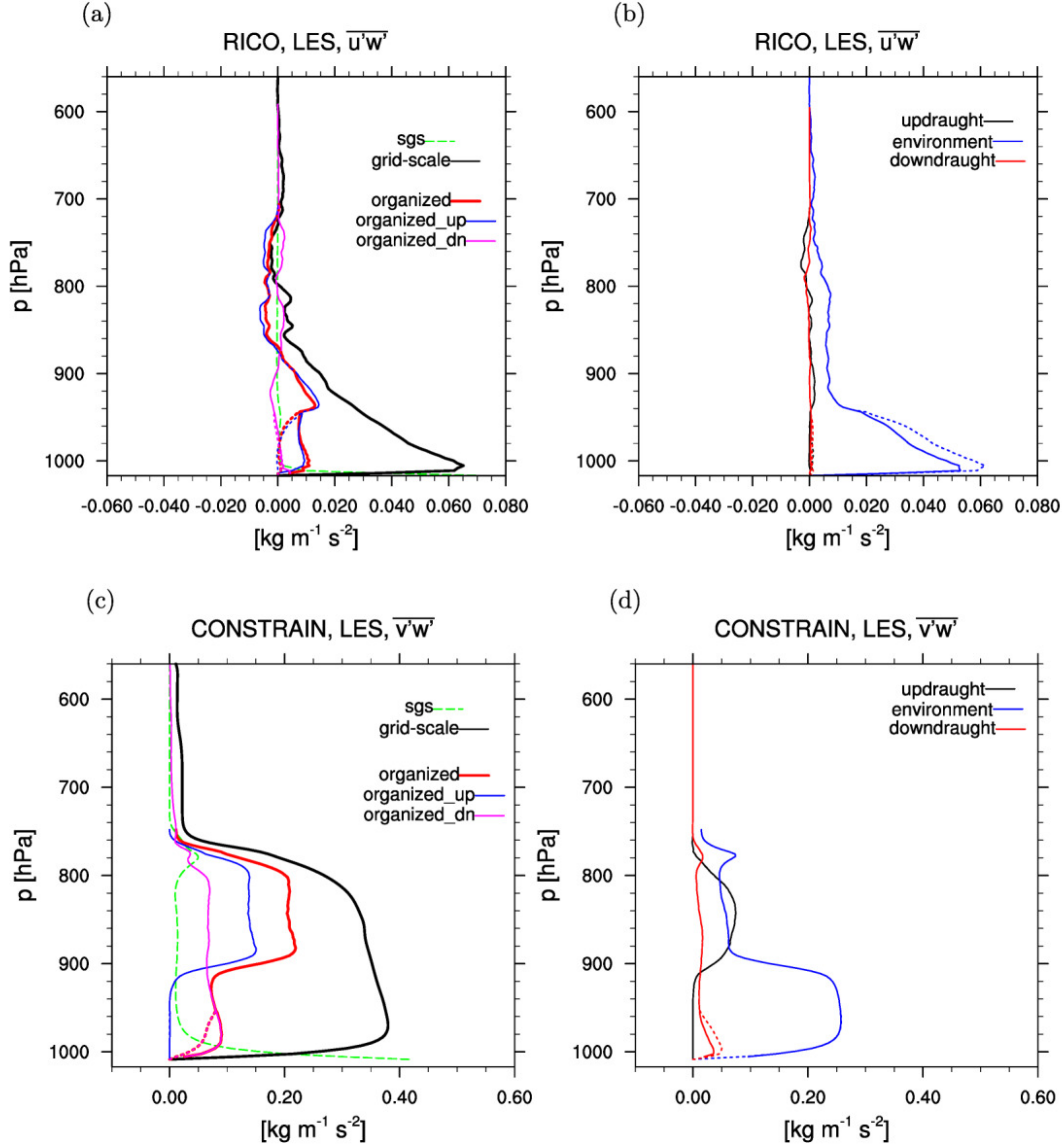


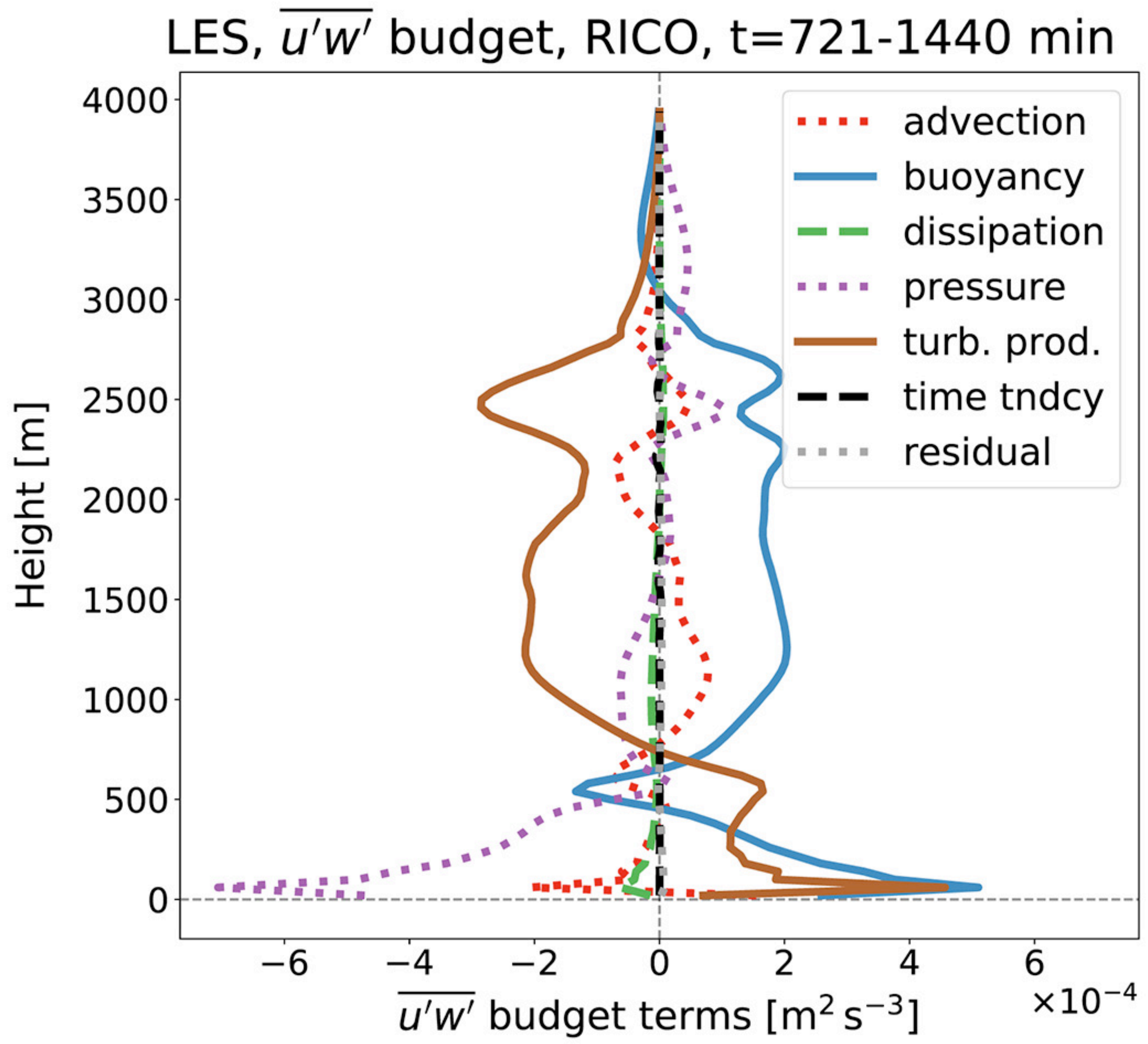


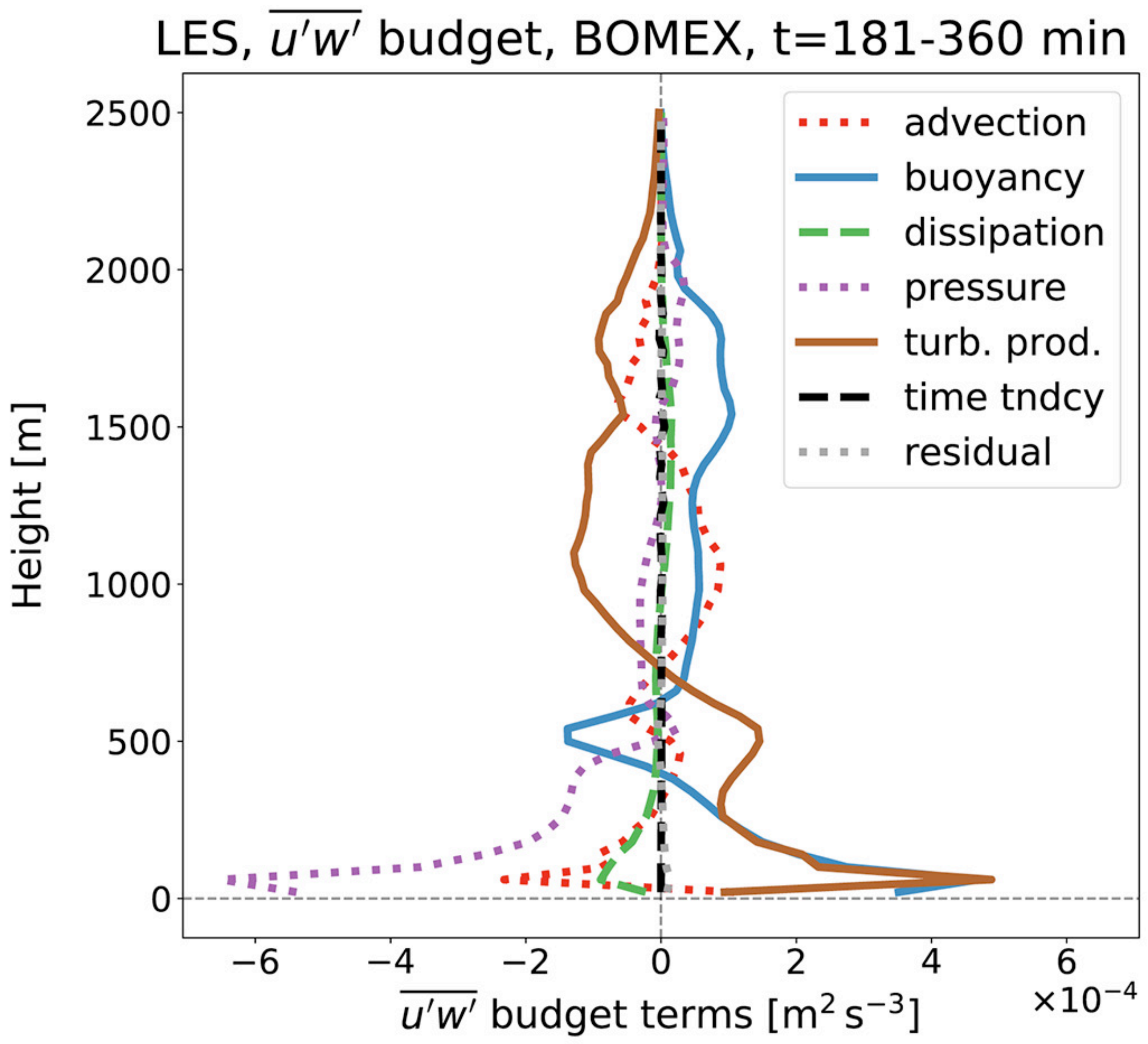
Backup slides

The maximum friction is introduced below cloud base



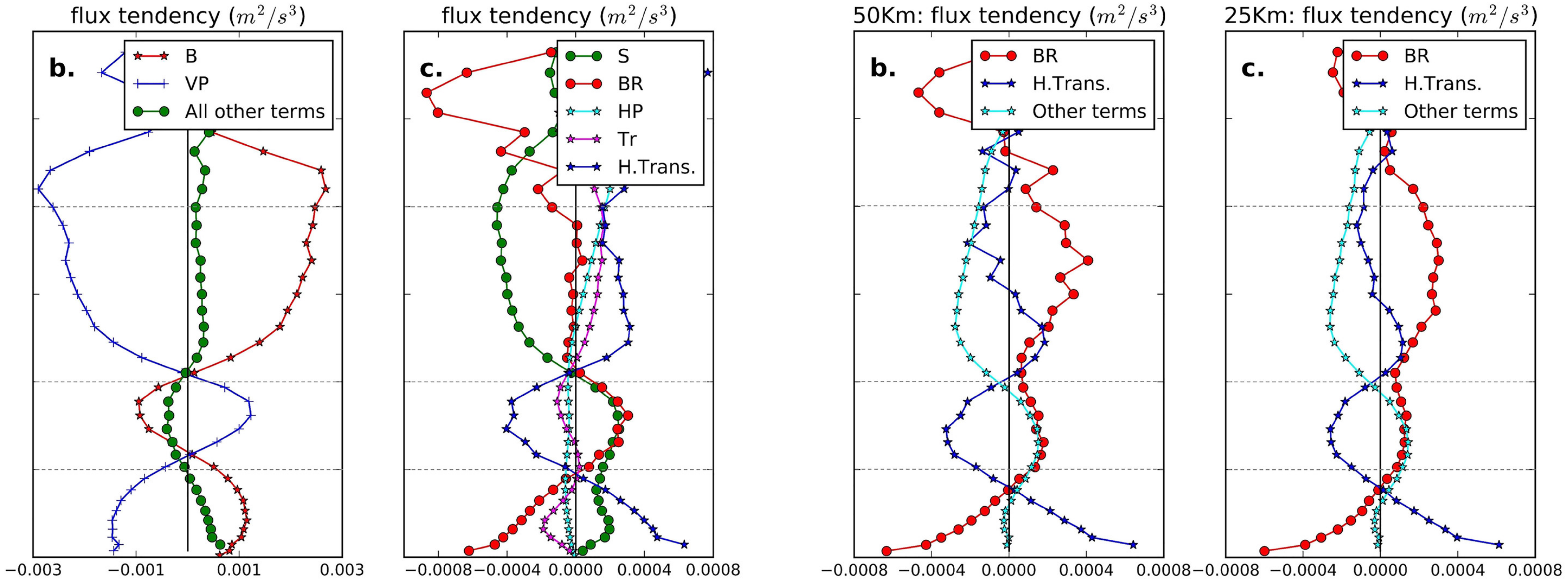

(a)
RICO, LES, $\overline{u'w'}$
sgs
grid-scale
organized
organized_up
organized_dn
p [hPa]
[kg m^{-1} s^{-2}]
(b)
RICO, LES, $\overline{u'w'}$
updraught
environment
downdraught
p [hPa]
[kg m^{-1} s^{-2}]
(c)
CONSTRAIN, LES, $\overline{v'w'}$
sgs
grid-scale
organized
organized_up
organized_dn
p [hPa]
[kg m^{-1} s^{-2}]
(d)
CONSTRAIN, LES, $\overline{v'w'}$
updraught
environment
downdraught
p [hPa]
[kg m^{-1} s^{-2}]





$$\frac{\partial \overline{u'w'}}{\partial t} = \underbrace{-\overline{w'^2}\frac{\partial \bar{u}}{\partial z}}_{\text{Turb Prod}} + \underbrace{\frac{g}{\theta_{vs}}\overline{u'\theta_v'}}_{\text{Buoy Prod}} - \underbrace{C_7\frac{g}{\theta_{vs}}\overline{u'\theta_v'}}_{\text{Press-Buoy}} - \underbrace{\frac{C_6}{\tau}\overline{u'w'}}_{\text{Return to Isotropy}} - \underbrace{\frac{1}{\rho}\frac{\partial \rho\overline{w'^2u'}}{\partial z}}_{\text{Turb Advection}} .$$

Buoyancy generation of flux largely compensated by vertical pressure perturbations

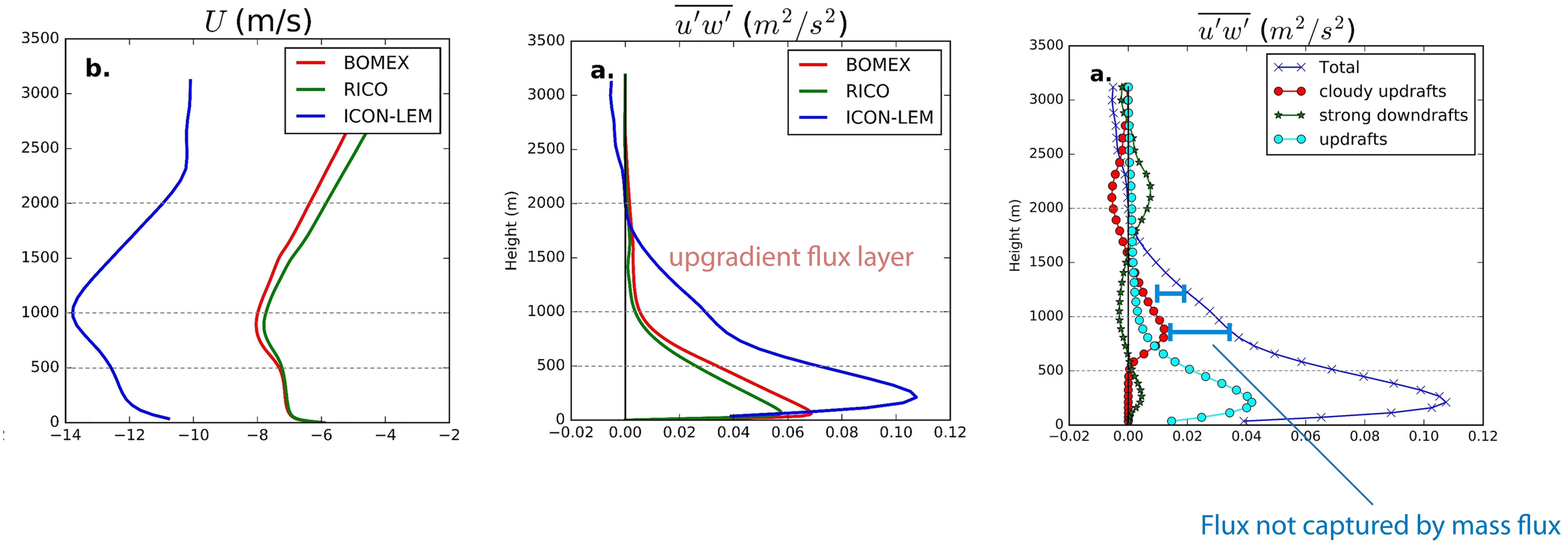


$$BR = \frac{g}{\overline{T_v}}\overline{u'T_v'} - \overline{\frac{u'}{\overline{\rho}}\frac{\partial p'}{\partial z}}$$

B VP

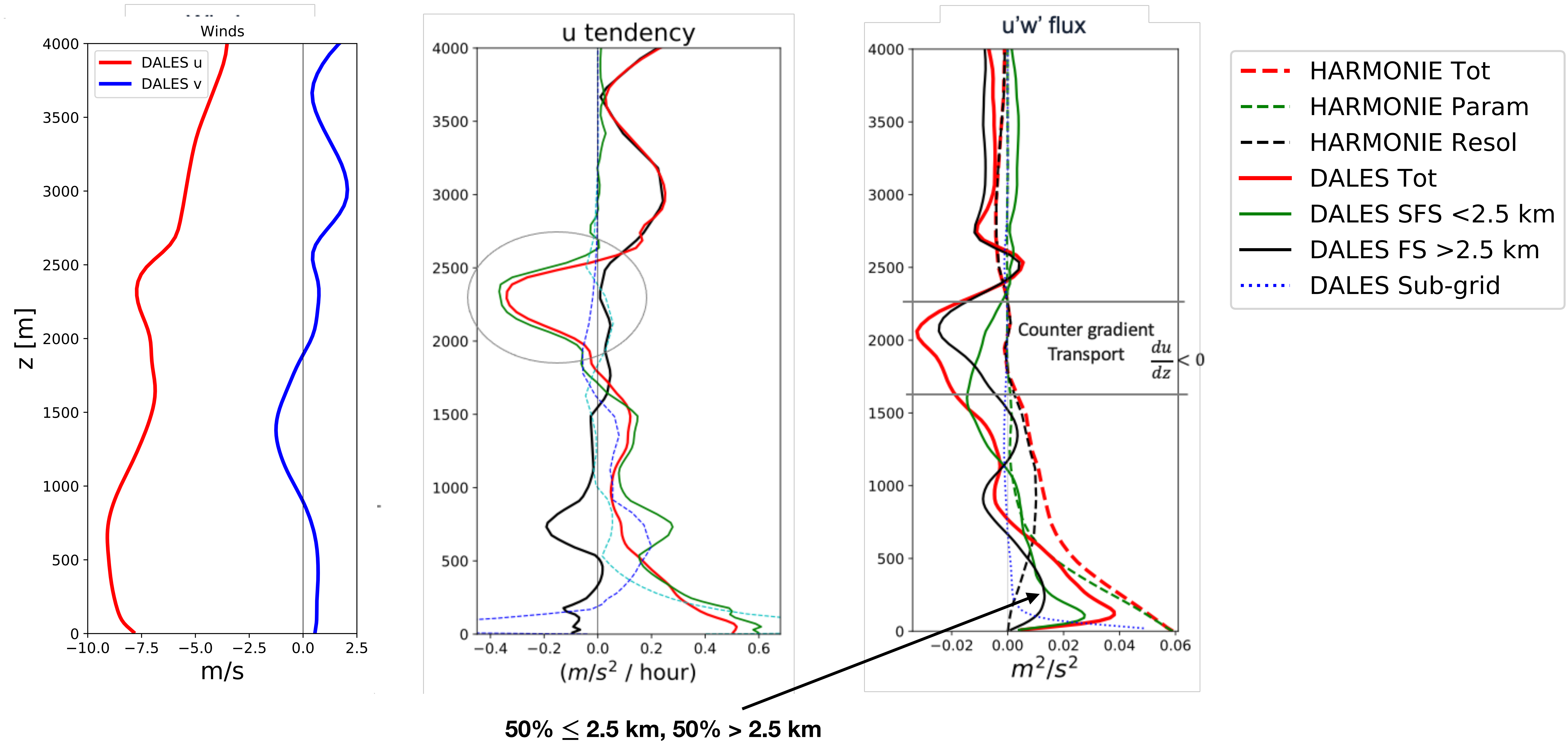
Dixit et al (2020): NARVAL with ICON-LEM on 150 km x 150 km x xx km, Δx = 125m

Mass flux approach does not suffice (environmental flux is significant) and pressure gradients matter for in-cloud momentum



Dixit et al (2020): NARVAL with ICON-LEM on 150 km x 150 km x xx km, Δx = 125m

Mesoscale momentum transport important for upgradient transport and acceleration near cloud tops, but also in the mixed-layer



Figures by: Alessandro Savazzi

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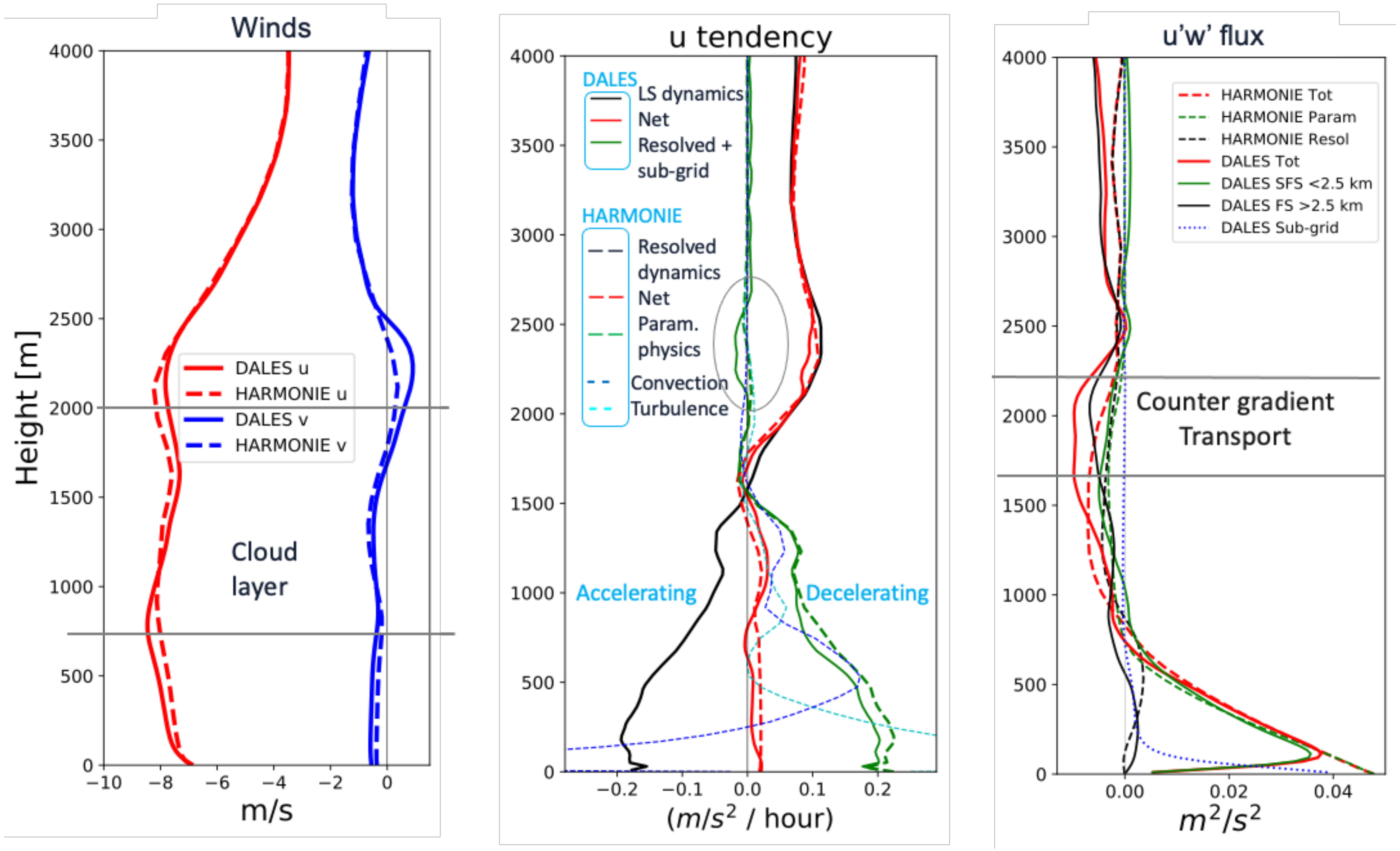

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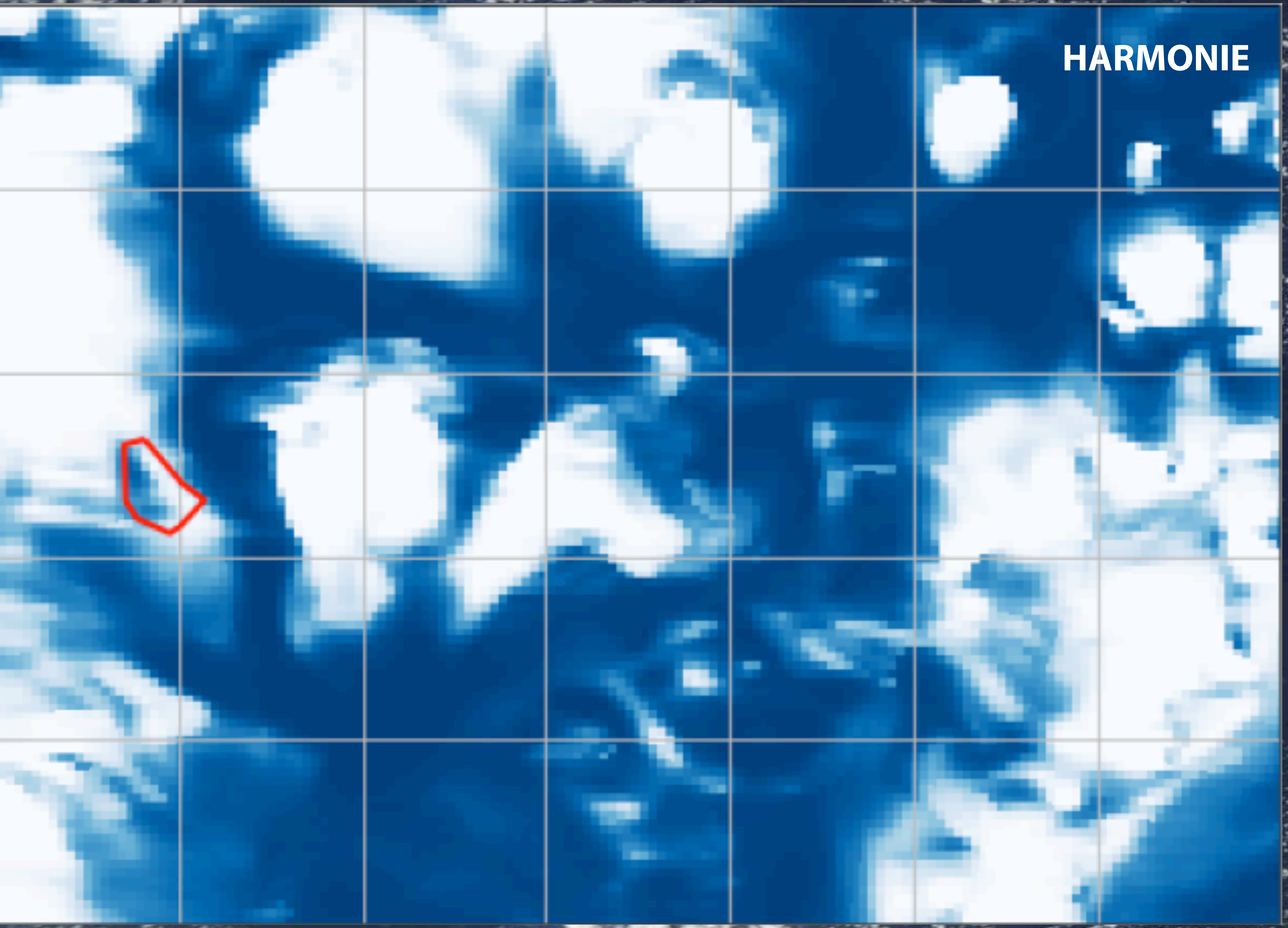
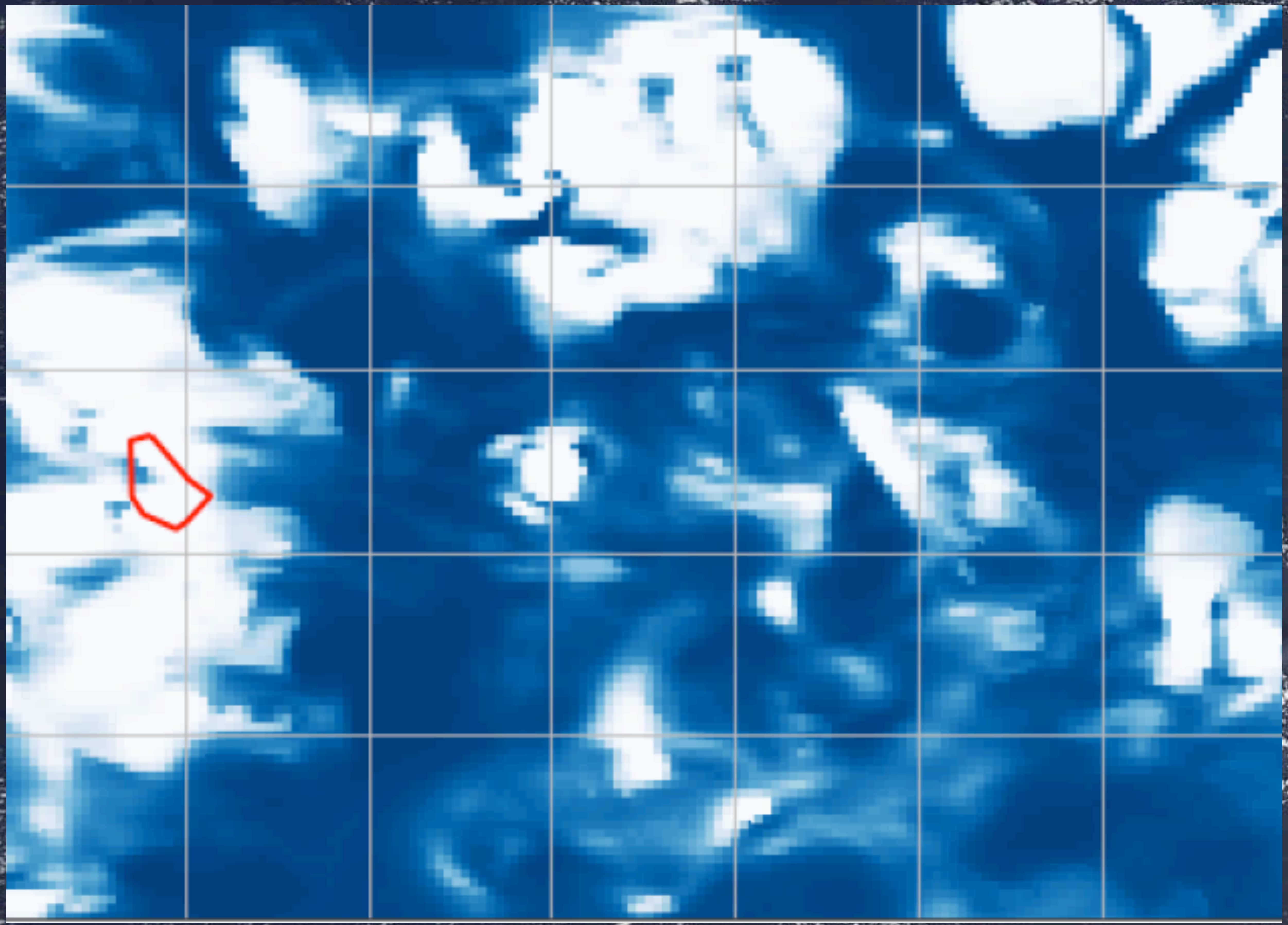


no shallow convective momentum transport



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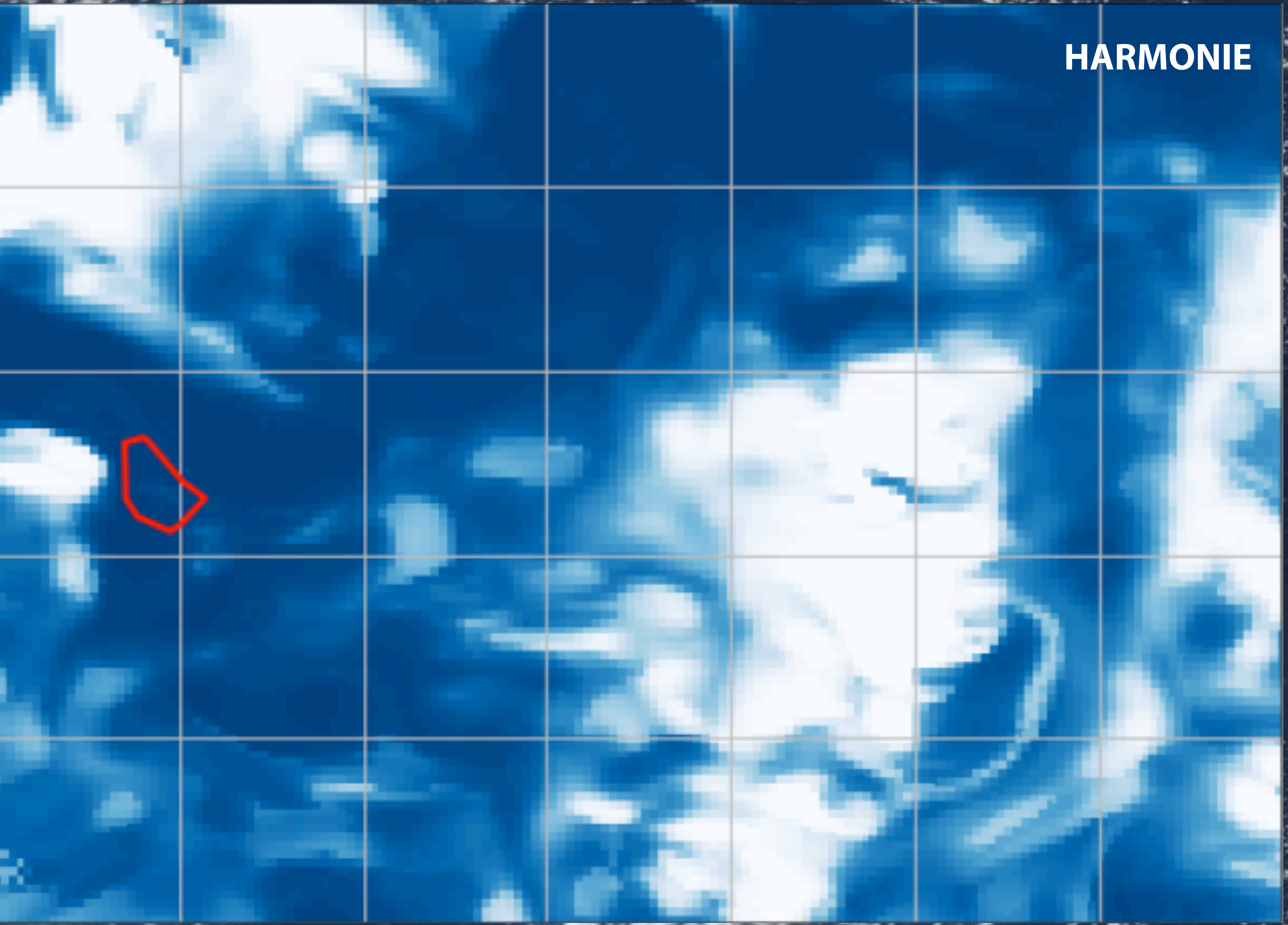

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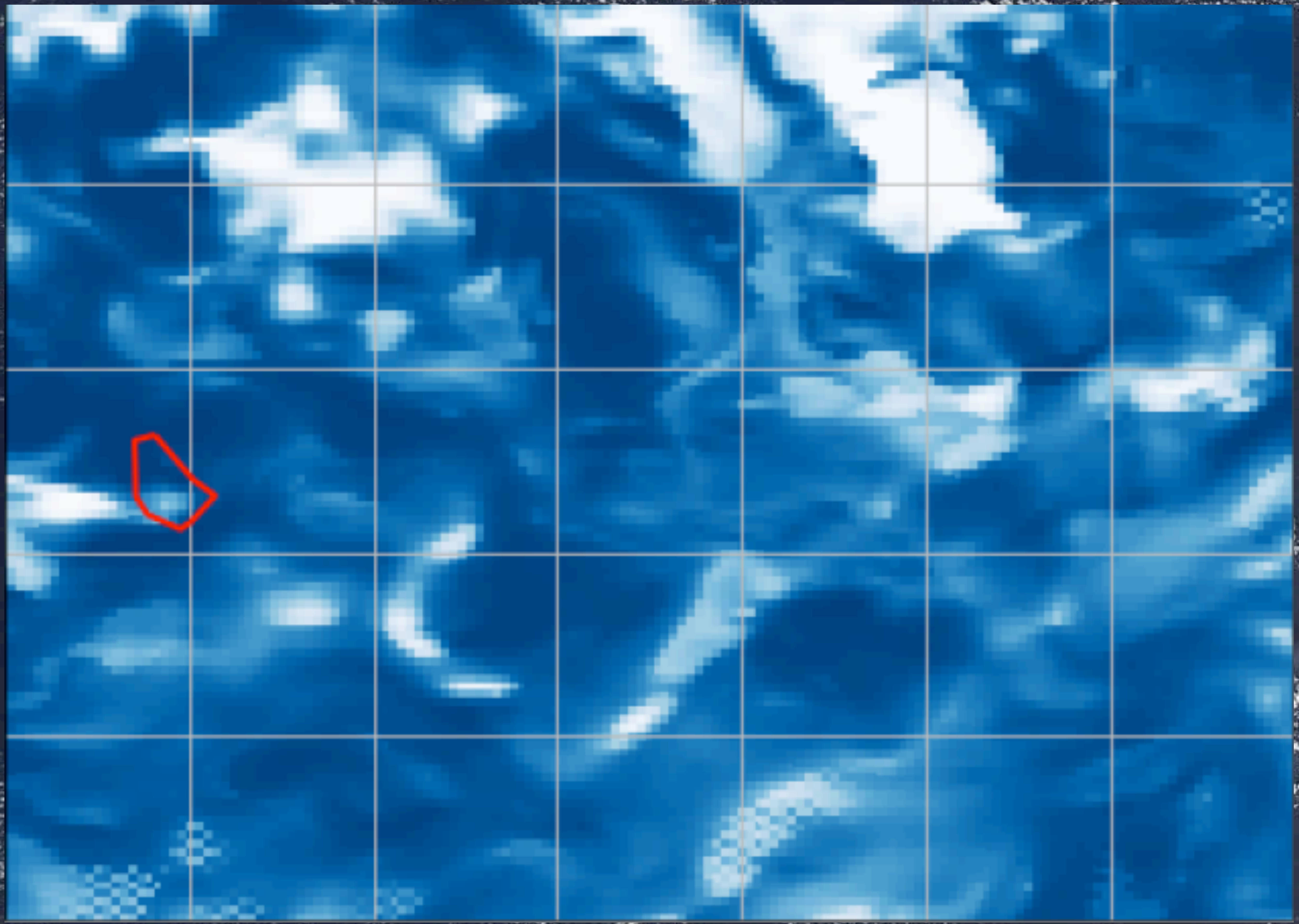

February 4, 2020 - 18 UTC

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