Turbulenz durch Konvektion und Berge in Reiseflughöhe und der Grenzschicht – Vorhersage (ECMWF IFS) und Beobachtung (TEAMx Kampagne)

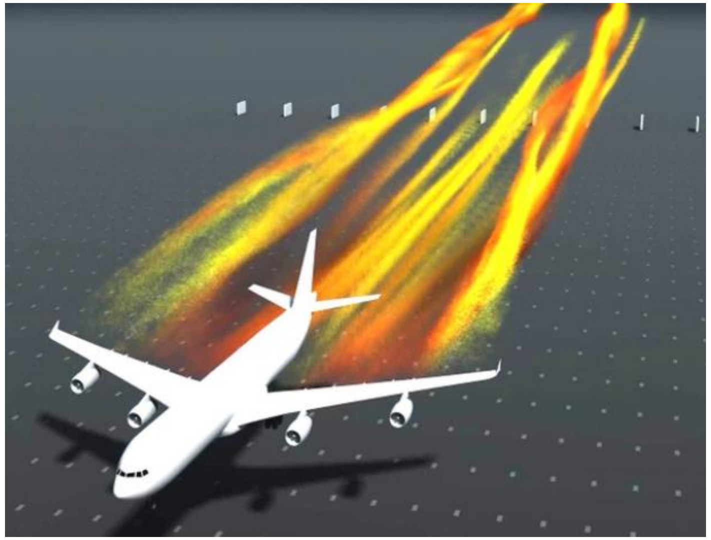
Sonja Gisinger, Andreas Dörnbrack

Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

DLR

Turbulenzforschung am DLR Institut für Physik der Atmosphäre

- Prozessverständnis
- Sicherheit im Flugverkehr
- hochaufgelöste Turbulenzsimulationen in der Grenzschicht (komplexes Gelände, Windenergie)
- einzigartige flugzeuggetragenen Beobachtungen
- Zusammenarbeit mit dem Europäischen Zentrum für mittelfriste Wettervorhersage (ECMWF) im Bereich der Turbulenzvorhersage



Turbulenz im Flugverkehr

Turbulence Safety Research report 2021 (National Transport Safety Board, NTSB):

- Turbulenz ist immer noch eine Hauptursache für Unfälle und Verletzungen im regulären planmäßigen zivilen Flugverkehr (2009-2018: 37.6%)
- Anschnallen ist der beste Schutz vor (schweren) Verletzungen
- Quellen: Konvektion, Windscherung, Gebirgswellen, Wirbelschleppe
- Einteilung in light, moderate, severe, extreme
- Flugzeugunabhängige Turbulenzgröße: Eddy Dissipation Rate (EDR)

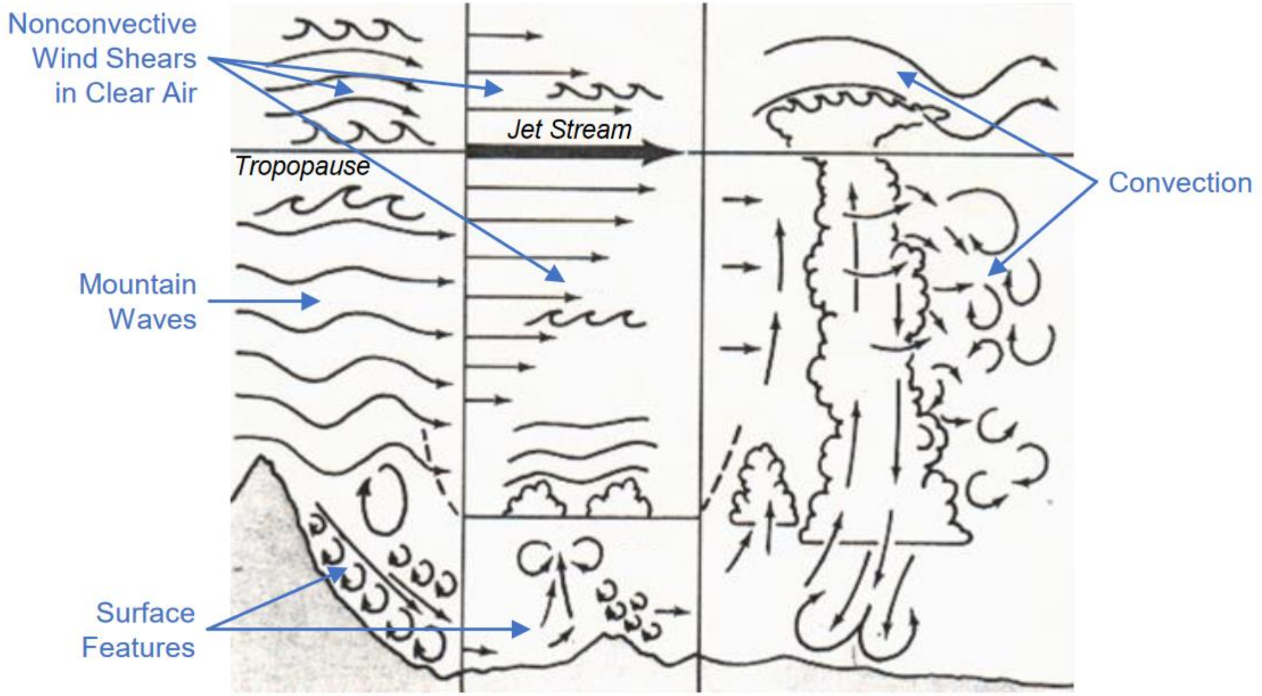


Figure 1. Illustration showing sources of turbulence (adapted from Lester 1994).

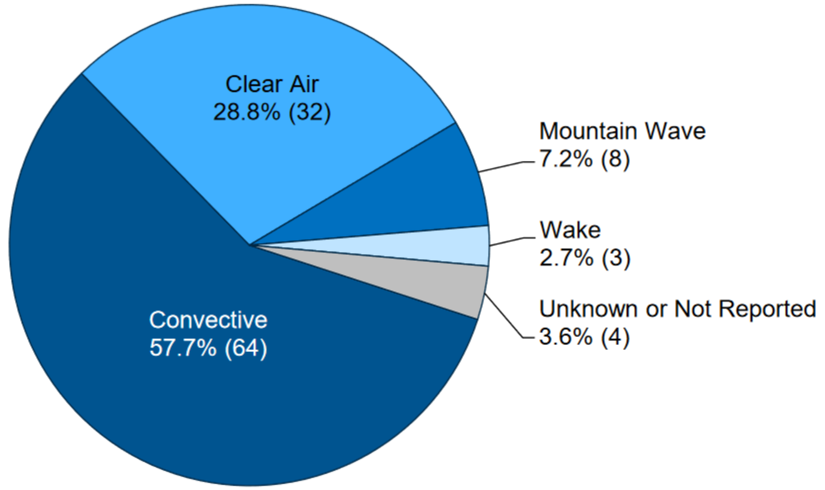
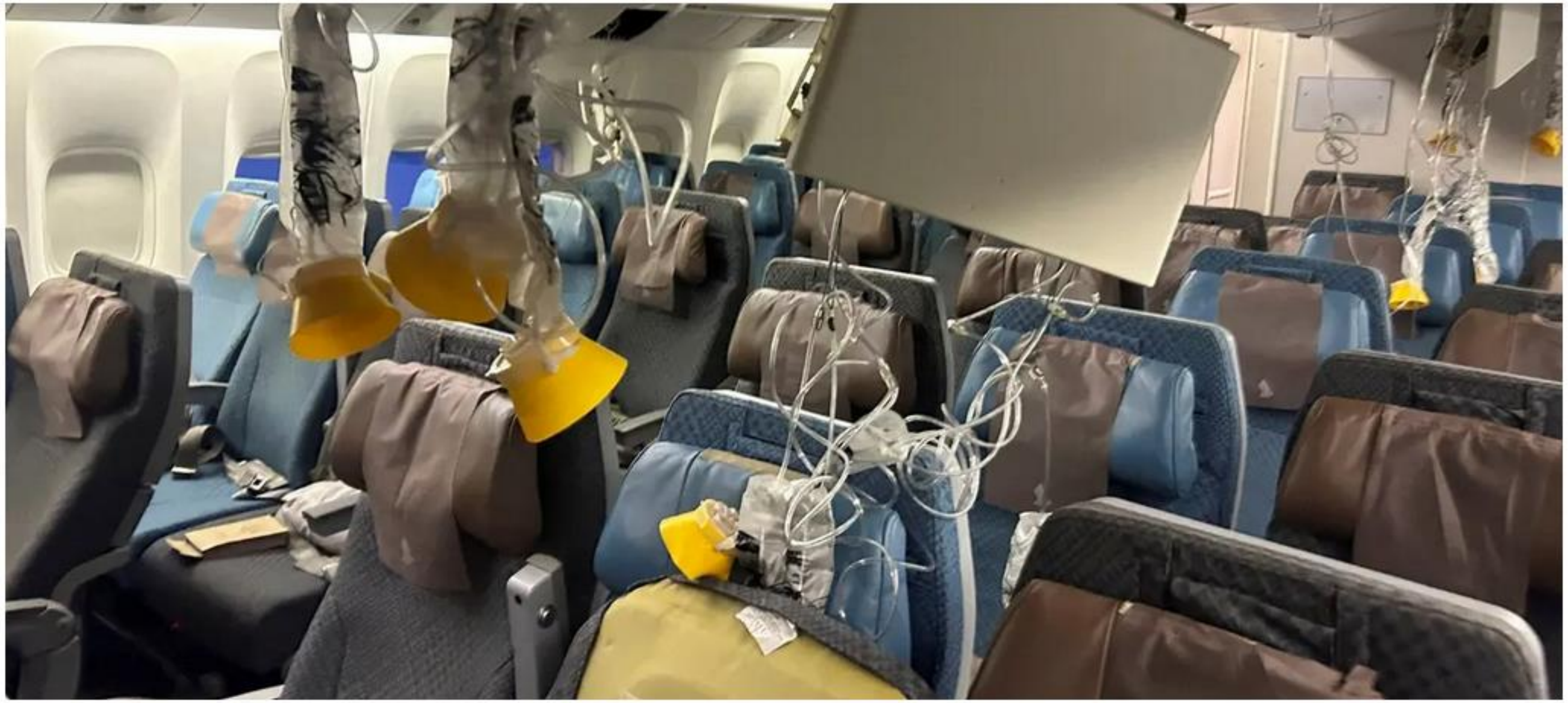


Figure 7. Turbulence-related Part 121 accidents by turbulence type, 2009–2018.

21. May 2025: Singapore Airlines Flug SQ321 geriet über Myanmar in schwere Turbulenzen

tagesschau   Sendung verpasst?

Startseite ▸ Ausland ▸ Asien ▸ Ein Toter nach schweren Turbulenzen auf Flug nach Singapur



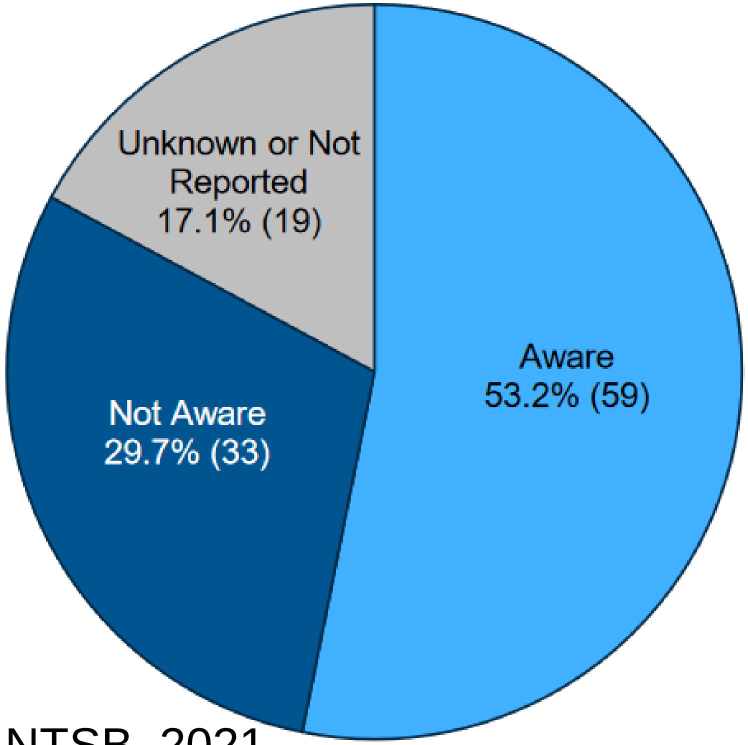
Flug von London nach Singapur

Ein Toter nach schweren Turbulenzen

Stand: 21.05.2024 16:13 Uhr

Nach schweren Turbulenzen während eines Passagierflugs von London nach Singapur ist ein Mensch ums Leben gekommen. Die Maschine von Singapore Airlines musste außerplanmäßig in Bangkok zwischenlanden.

Turbulence is mostly critical when experienced unexpectedly



NTSB, 2021

Figure 12. Flight crew awareness of turbulence risk prior to turbulence-related Part 121 accidents, 2009–2018.

11 Aug 2024

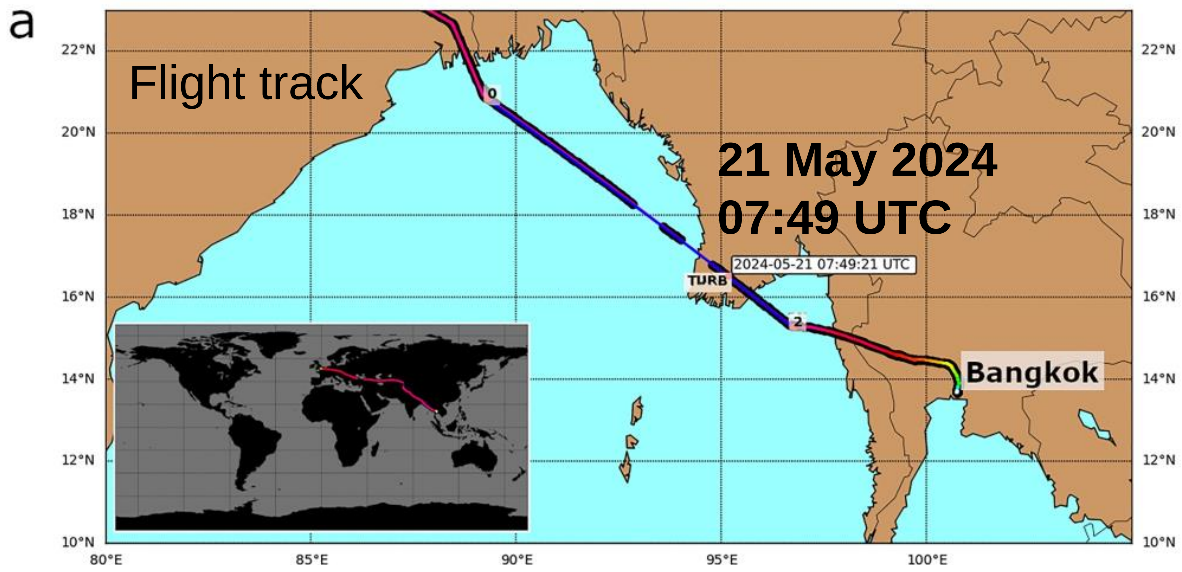
BR238:
incident during meal service
at cruising altitude

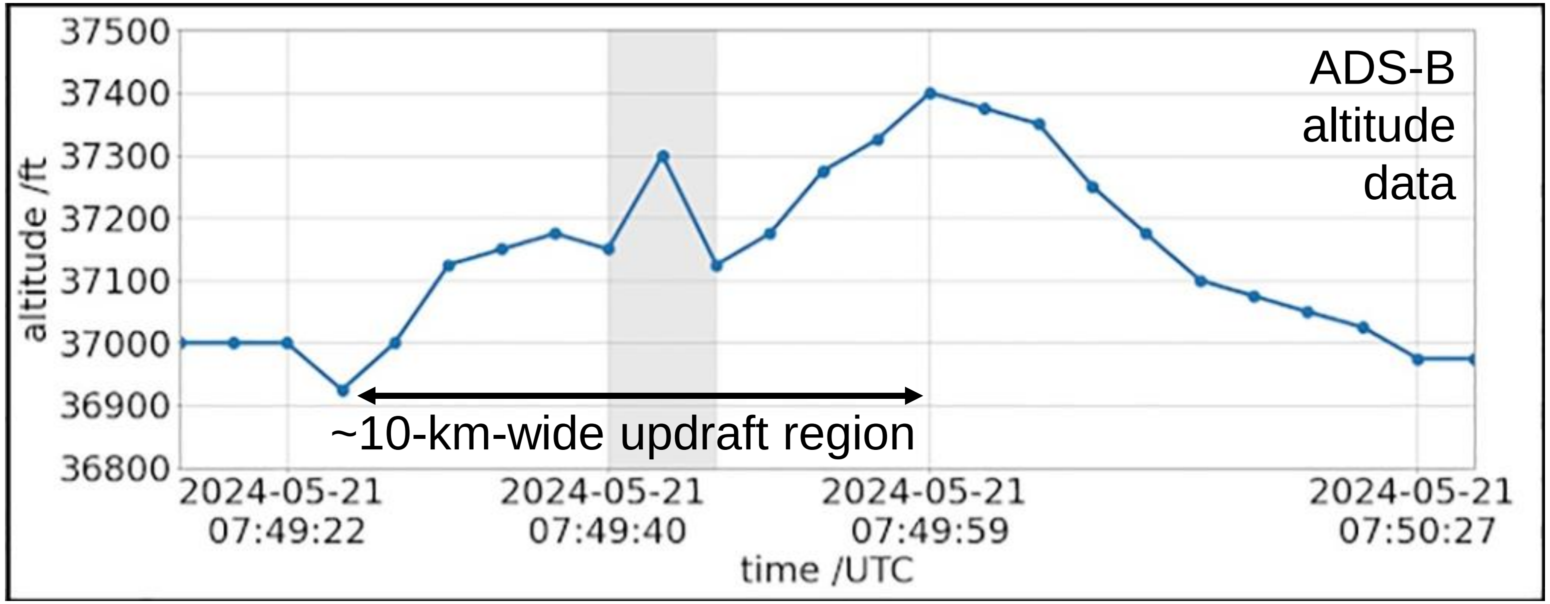
12 Nov 2024

LH511:
brief but severe turbulence

Turbulence encounter by Singapore Airlines flight SQ321 was one among many.

Rapid changes in aircraft altitude during the turbulence encounter





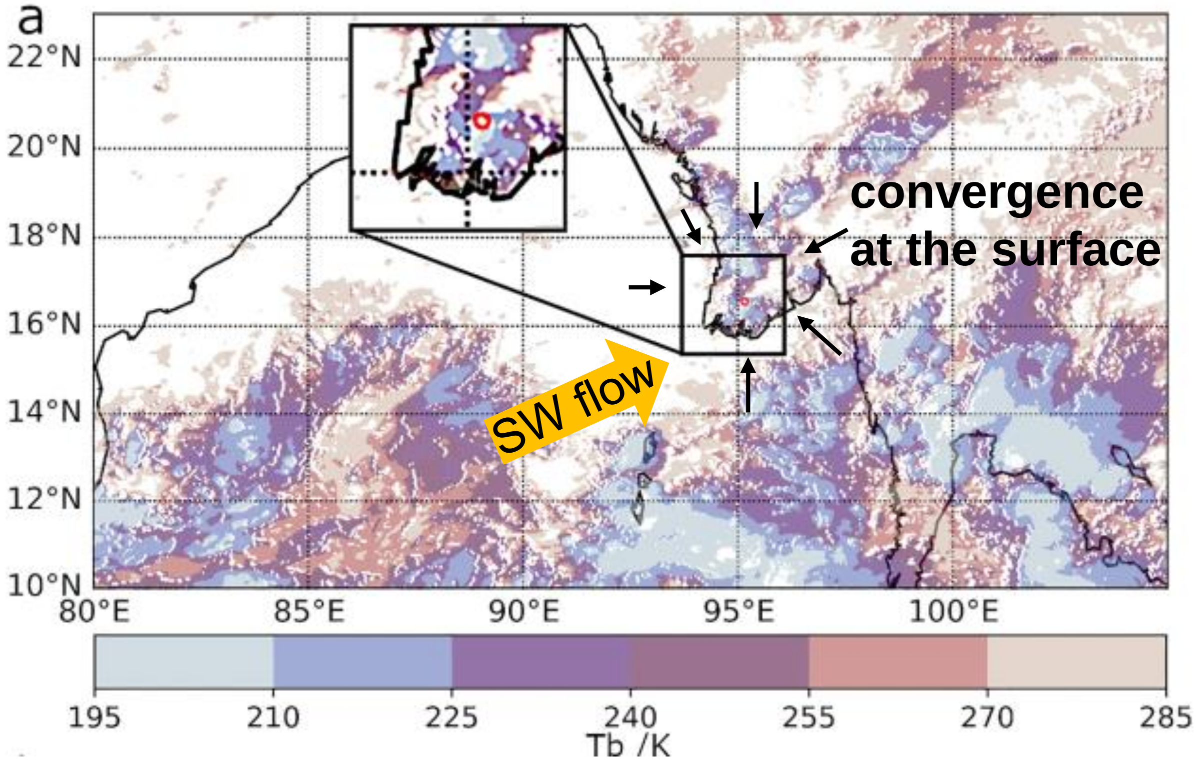
In total:
362 ft (110 m) in 37 s

(Mountain Wave incident HALO over Iceland in 2016:
50 m in 15 s)

Gisinger, S., Bramberger, M., Dörnbrack, A., & Bechtold, P. (2024). Severe convectively induced turbulence hitting a passenger aircraft and its forecast by the ECMWF IFS model. *Geophysical Research Letters*, 51, e2024GL113037. https://doi.org/10.1029/2024GL113037

Meteorological conditions and the presence of convection

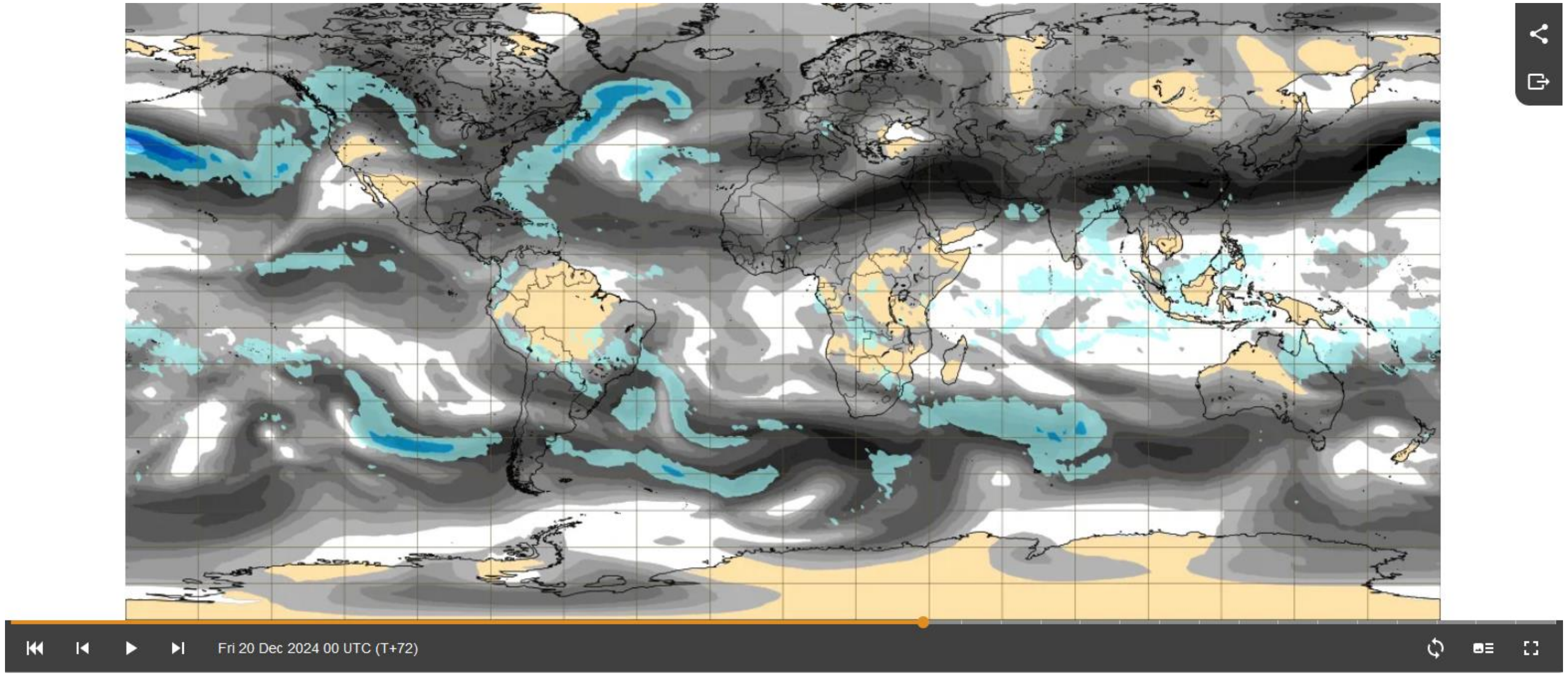
Himawari-8 brightness temperature showing convection in the area at 8 UTC (15:30 LT)

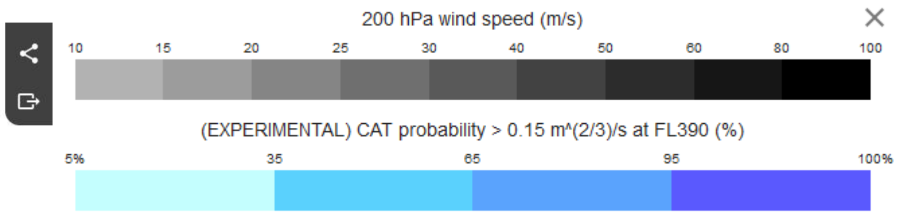


Preliminary report (29 May 2024): *"...the aircraft was passing over the south of Myanmar at 37,000 ft and likely flying over an area of developing convective activity."*

ECMWF Turbulenzvorhersage

- Vorhersageprodukt (EDR Index) wurde über die letzten Jahre entwickelt
- seit Oktober 2021 im operationellen Betrieb verfügbar
- seit Juni 2023 auch als Ensemble Vorhersage basierend auf den 51 Ensemble Läufen mit gestörten Anfangsbedingungen





Find forecasts for your trips here and fasten your seatbelt

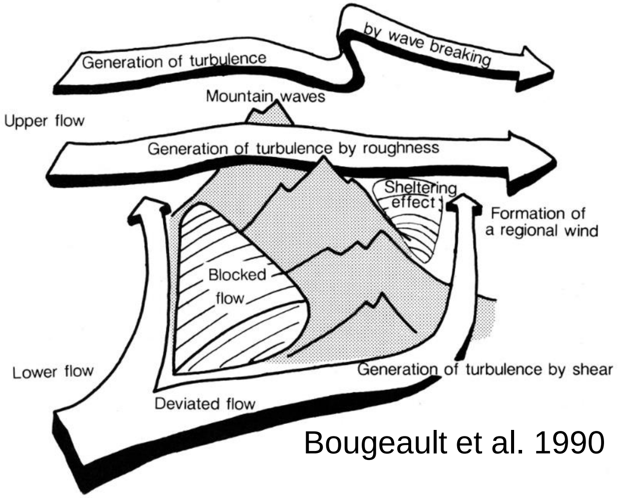
https://charts.ecmwf.int/?query=turbulence

ECMWF

ECMWF EDR Index is based on total dissipation rate (tendencies for horizontal momentum)

vertical diffusion scheme

- turbulent mixing 
- orographic wave drag
- orographic blocking



Bougeault et al. 1990

ECMWF EDR Index is based on total dissipation rate (tendencies for horizontal momentum)

vertical diffusion scheme + convective momentum transport + convective gravity wave drag

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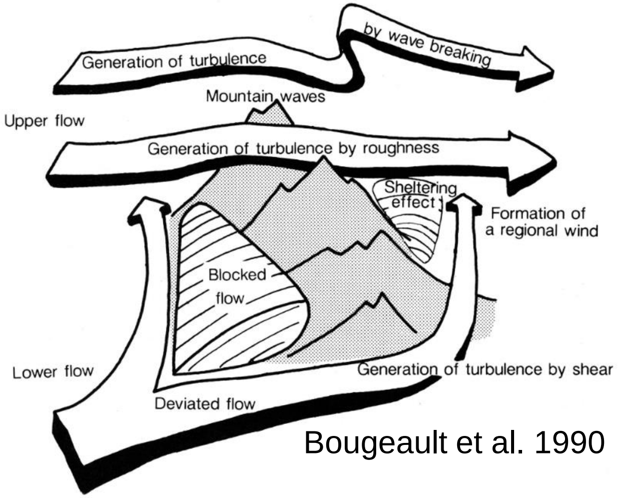
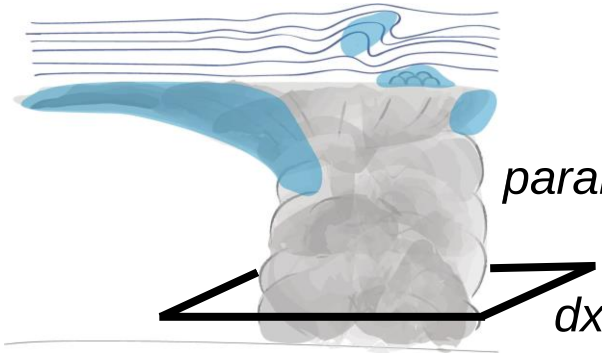


Bougeault et al. 1990

- convection parametrization

- non-orographic wave scheme



parametrized

$dx_{ECMWF\ IFS} = 9\ km$

Sharman and Trier, 2019

ECMWF EDR Index is based on total dissipation rate (tendencies for horizontal momentum)

vertical diffusion scheme + convective momentum transport + convective gravity wave drag

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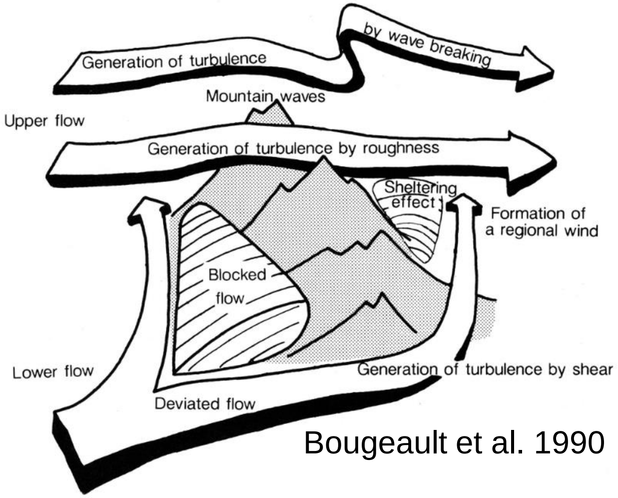

Bougeault et al. 1990

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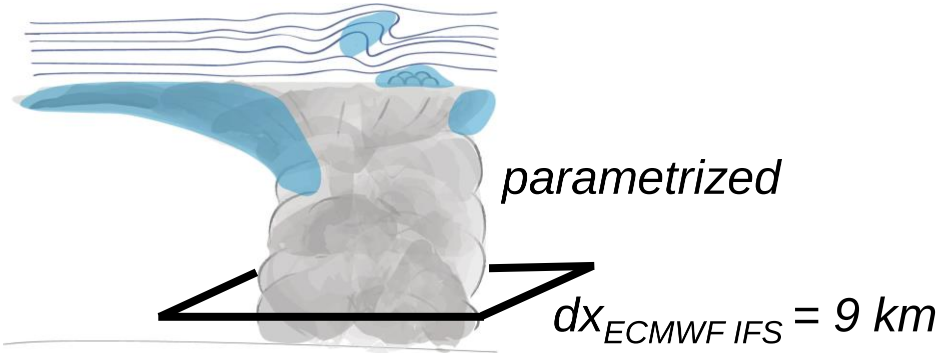

Sharman and Trier, 2019

= total dissipation rate (DISS) → EDR= 2/3 DISS

ECMWF EDR Index is based on total dissipation rate (tendencies for horizontal momentum)

vertical diffusion scheme + convective momentum transport + convective gravity wave drag

- turbulent mixing 
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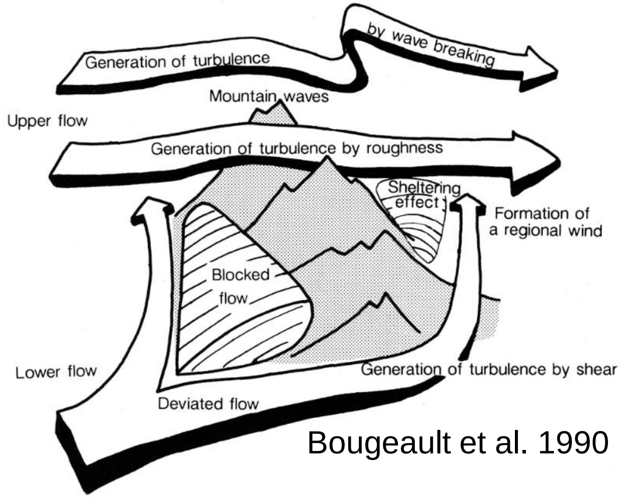
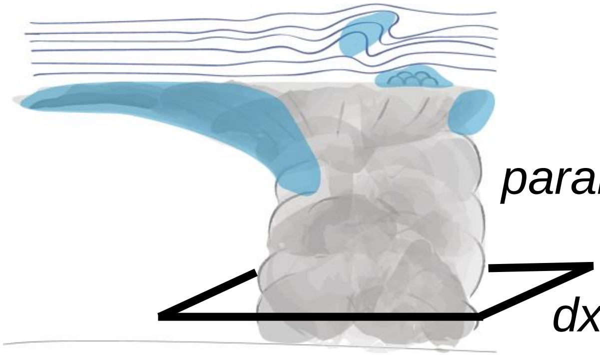
- orographic blocking



Bougeault et al. 1990

- convection parametrization



Sharman and Trier, 2019

- non-orographic wave scheme

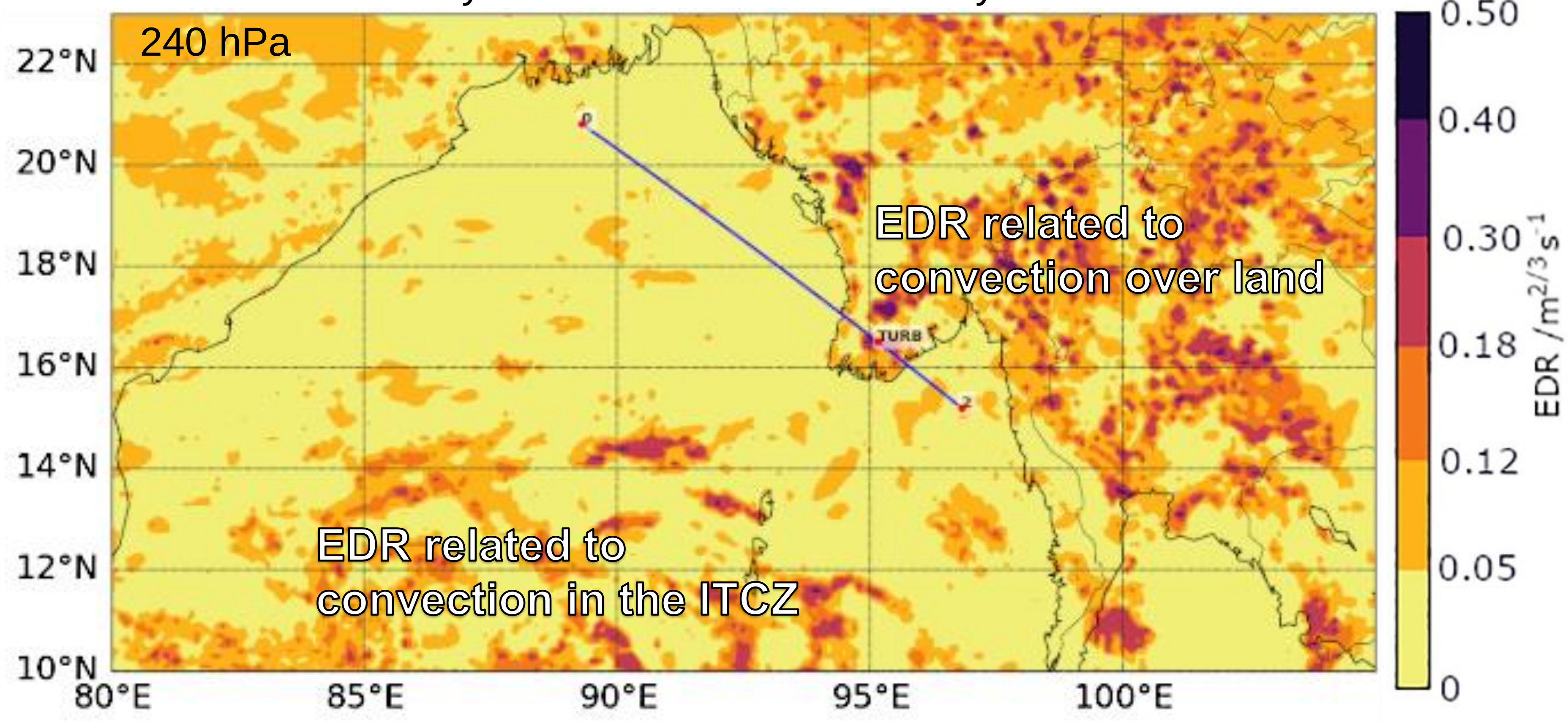
= total dissipation rate (DISS) → EDR= 2/3 DISS

51-member ensemble (ENS)

www.ecmwf.int

Reference run (HRES) of EDR Index initialized prior to departure of SQ321 indicates turbulence

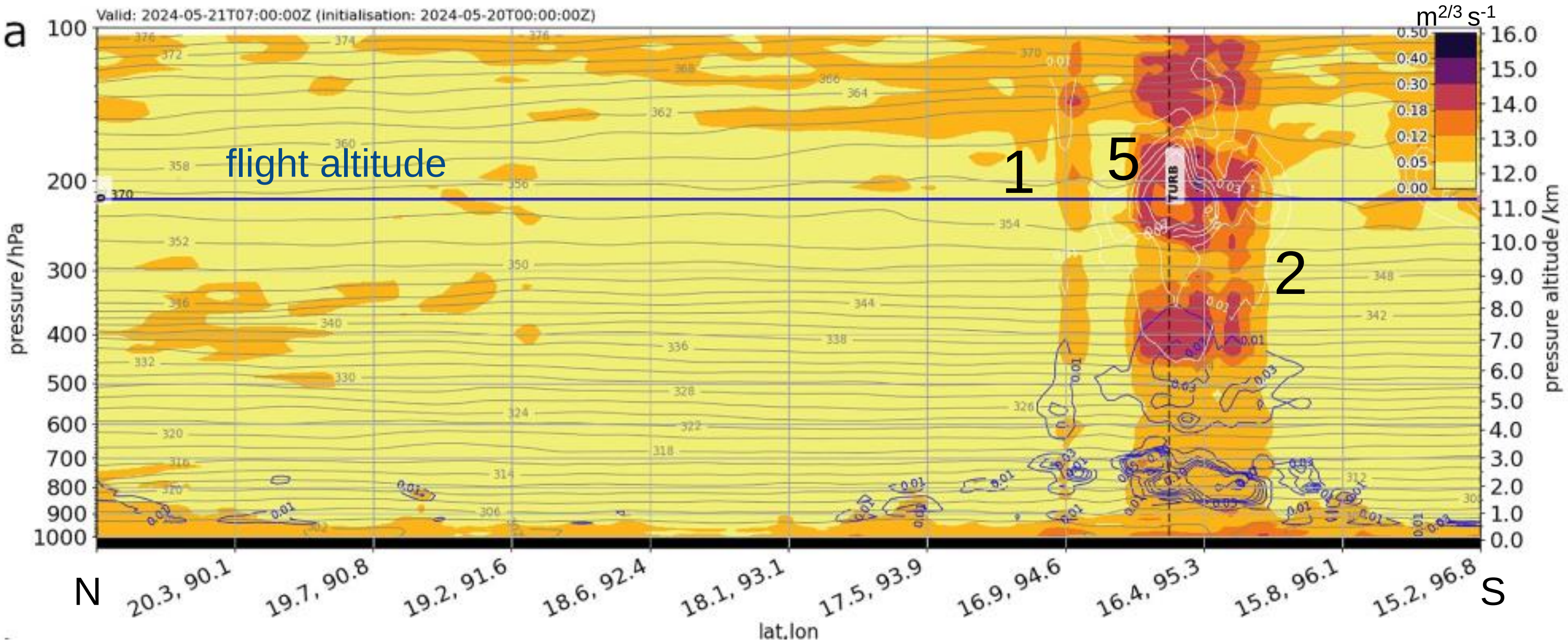
init: 20 May 2024 00 UTC **valid:** 21 May 2024 07 UTC



EDR for moderate or greater turbulence

Reference run (HRES) of EDR Index initialized prior to departure of SQ321 indicates turbulence

init: 20 May 2024 00 UTC **valid:** 21 May 2024 07 UTC

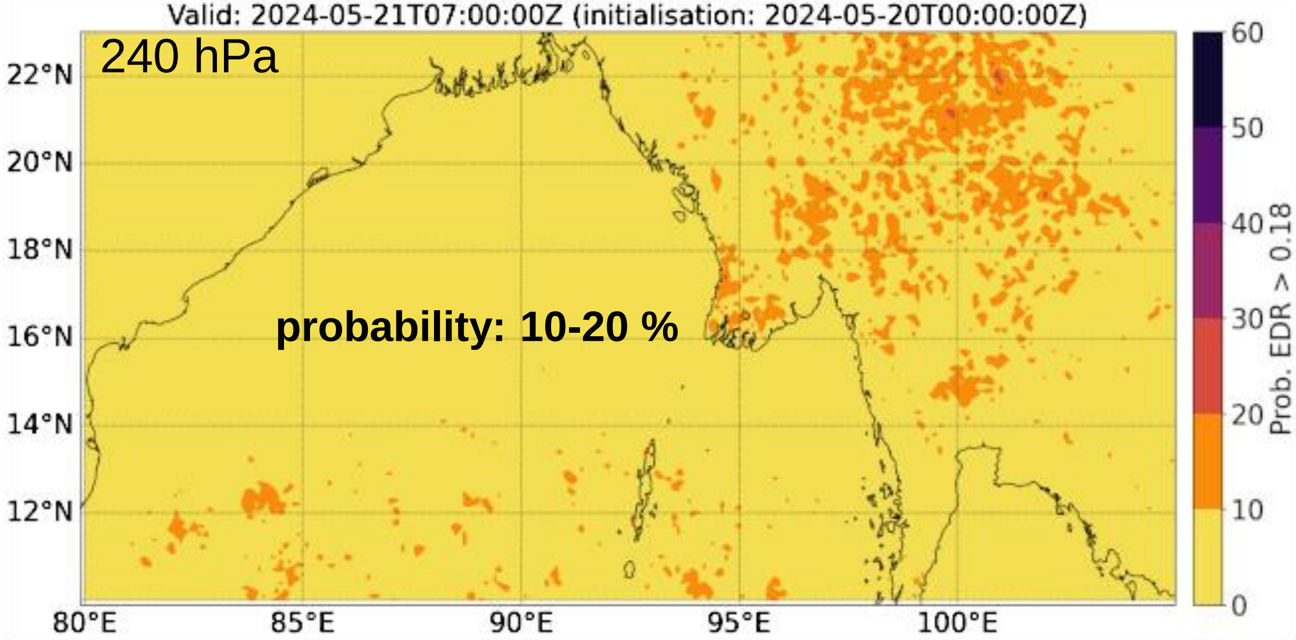


1. reduced stability in the upper troposphere over land (isolines of pot. temperature)
2. in-cloud and out-of-cloud turbulence (liquid/ice water content)
3. convective updraft in vertical velocity (underestimated in ECMWF IFS, not shown)
4. positive vertical shear of horizontal wind (isolines of horizontal wind speed, not shown)
5. enhanced EDR in mid- and upper troposphere and around flight level (FL370)

→ ingredients for out-of-cloud CIT and NCT were both present in the forecast

Ensemble forecast: probability for EDR > 0.18 $m^{2/3}$ s^{-1} is enhanced over land

lead time: +31 hours

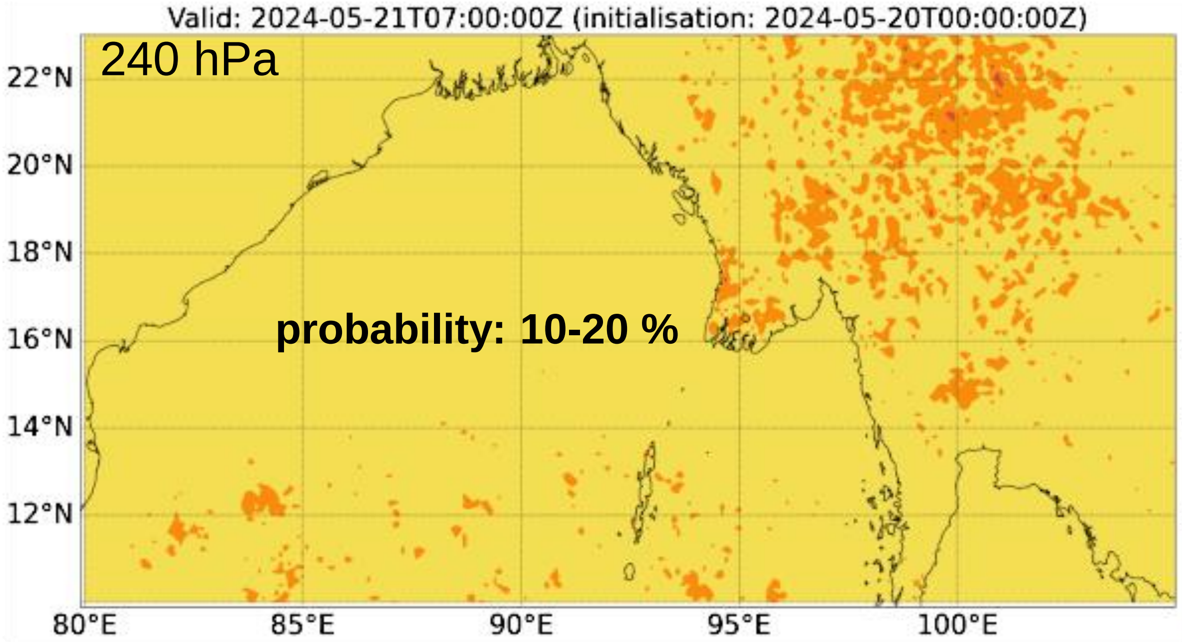


init: 20 May 2024 00 UTC **valid:** 21 May 2024 07 UTC

- probability at the location of the turbulence encounter increases to 36 % when +/-2 surrounding grid-points are considered

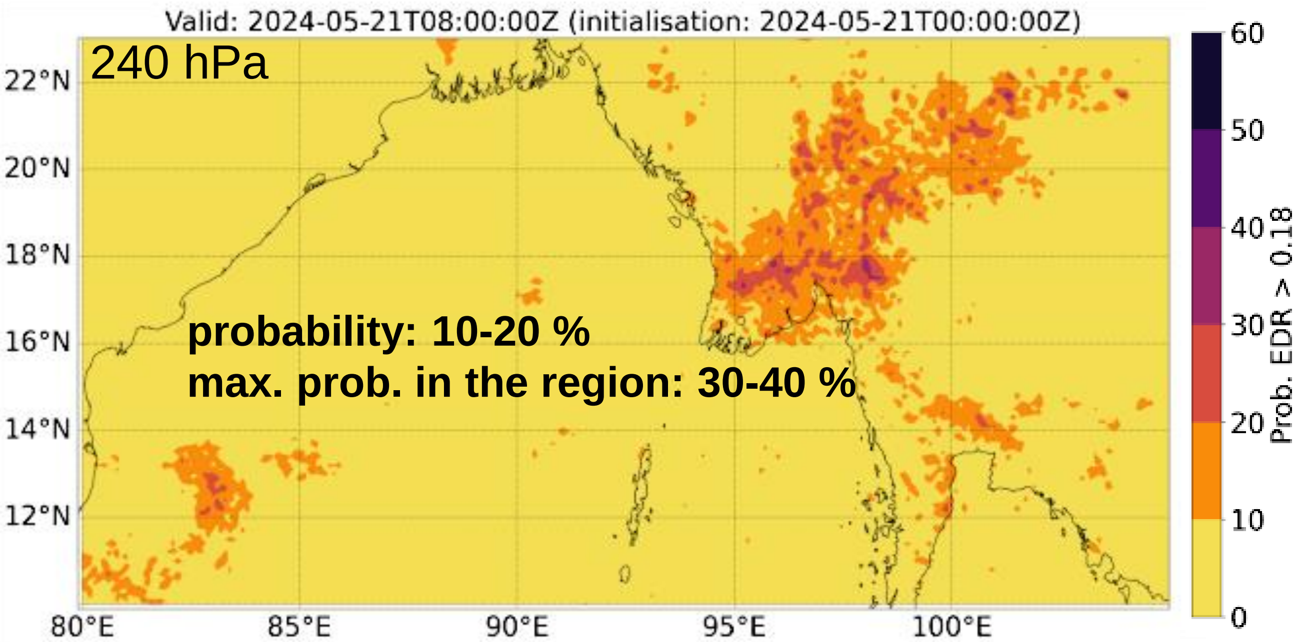
Ensemble forecast: probability for EDR > 0.18 $m^{2/3}$ s^{-1} is enhanced over land

lead time: +31 hours



init: 20 May 2024 00 UTC **valid:** 21 May 2024 07 UTC

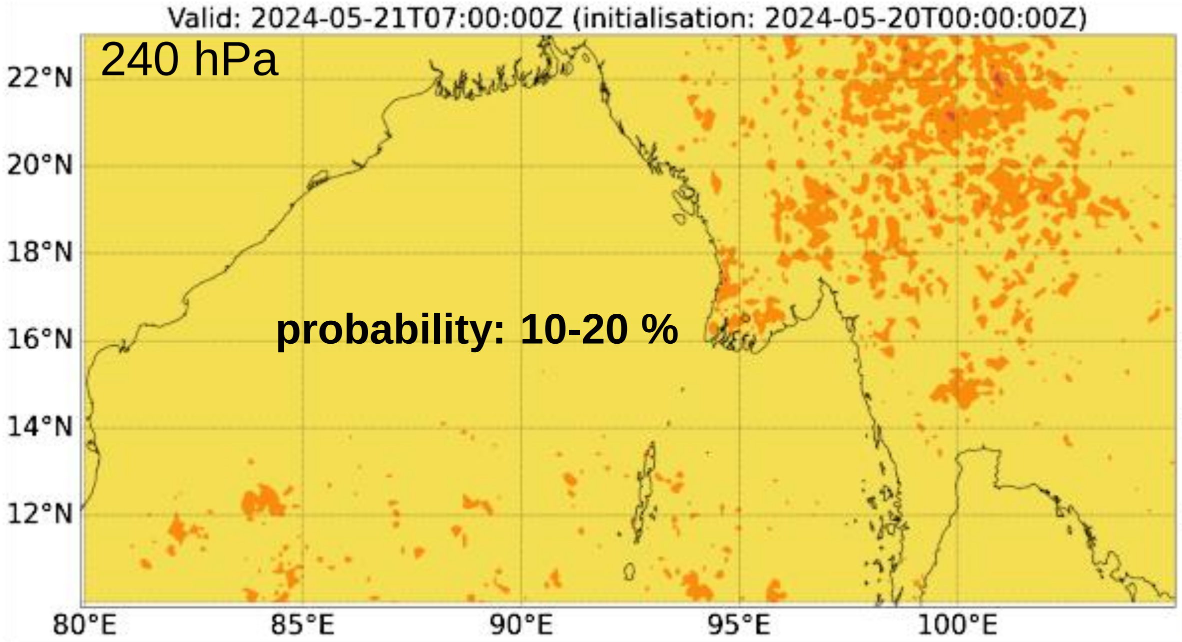
lead time: +8 hours



init: 21 May 2024 00 UTC **valid:** 21 May 2024 08 UTC

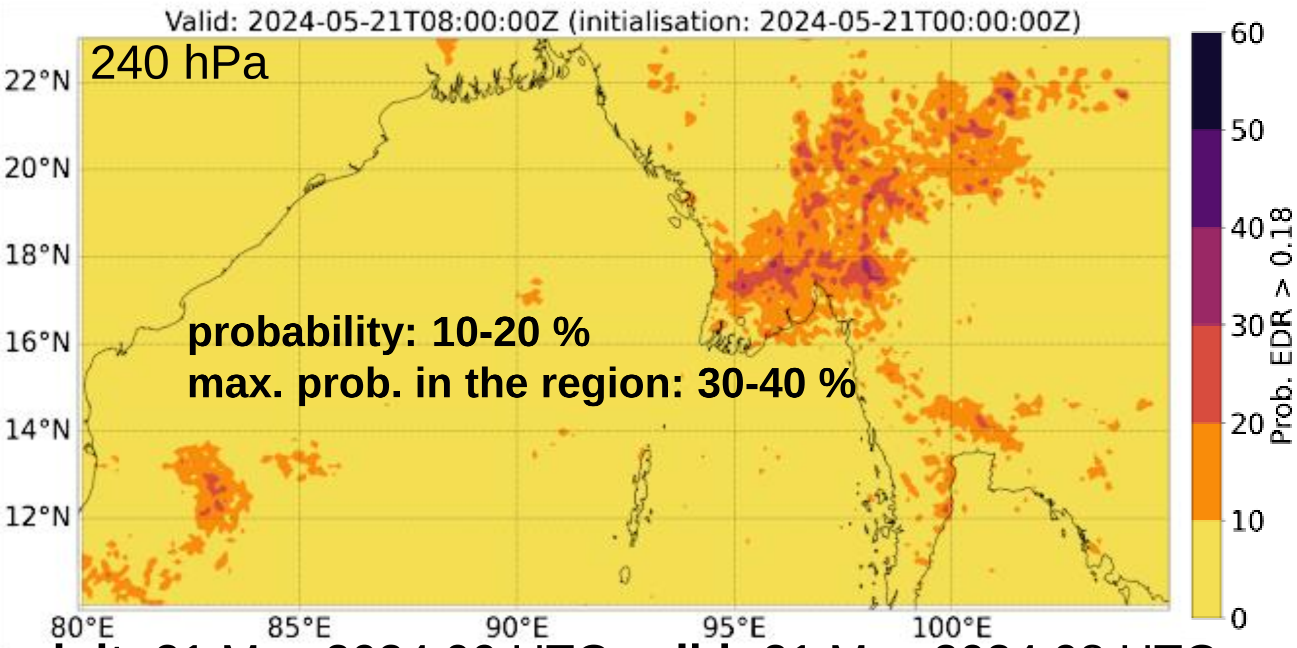
Ensemble forecast: probability for EDR > 0.18 $m^{2/3} s^{-1}$ is enhanced over land

lead time: +31 hours



init: 20 May 2024 00 UTC **valid:** 21 May 2024 07 UTC

lead time: +8 hours



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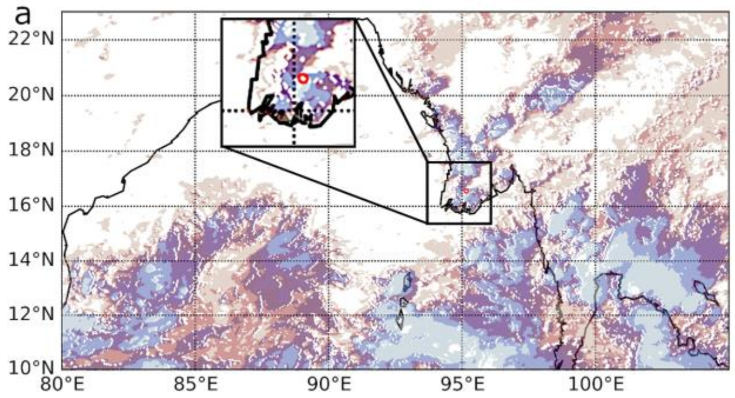
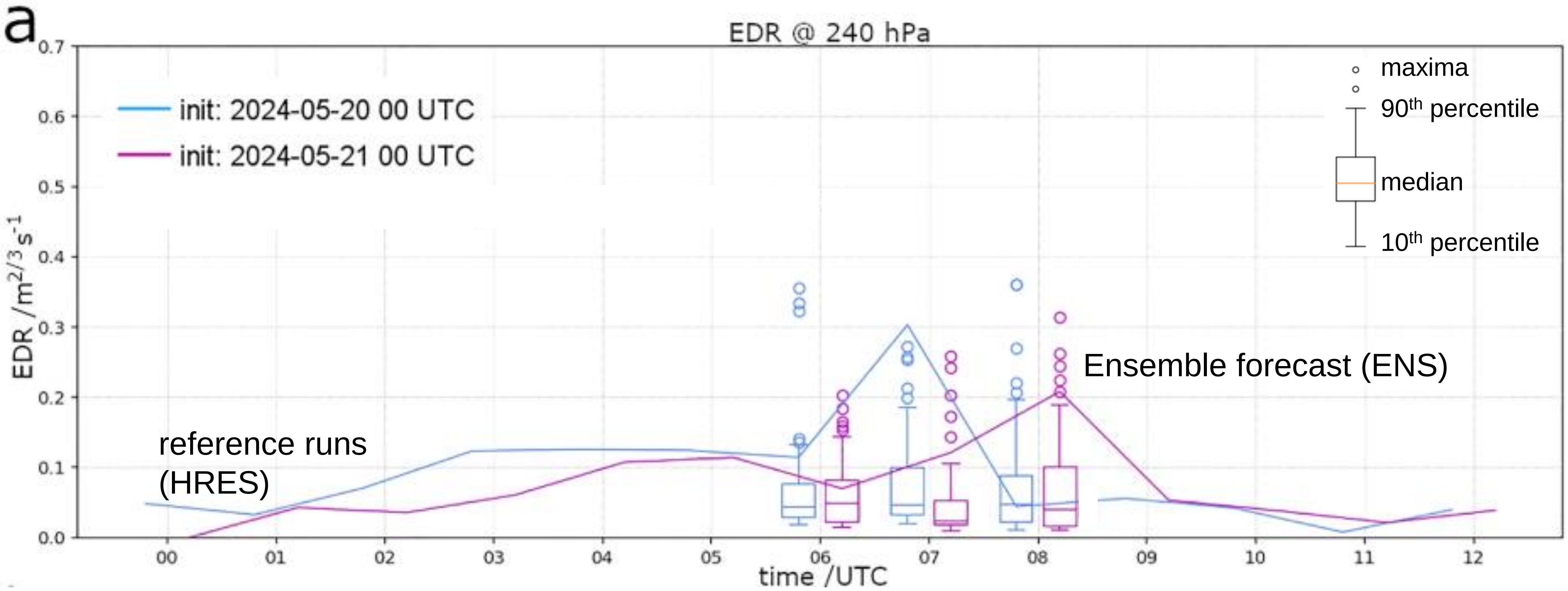
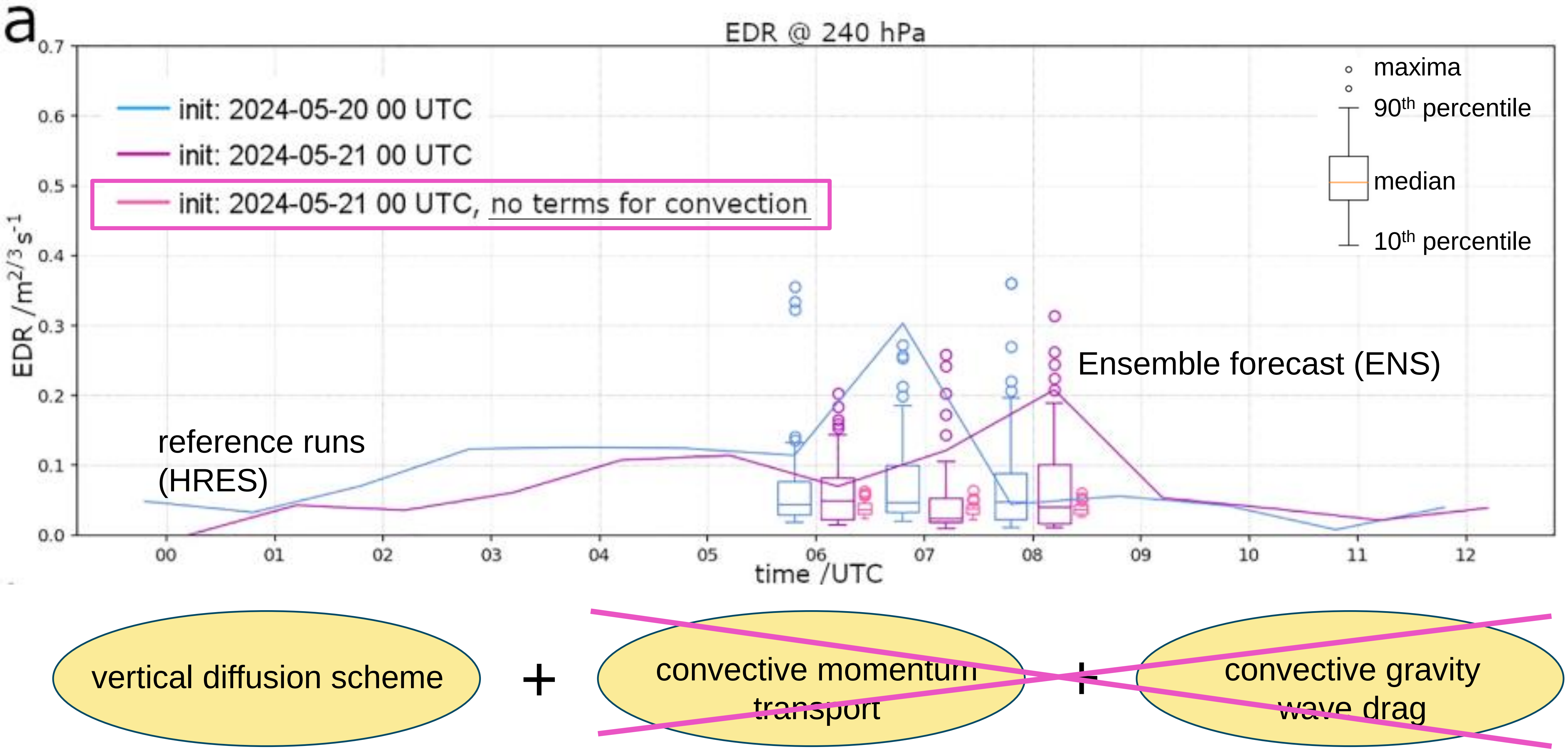


area at risk over land compares well with convection in the Himawari-8 satellite image

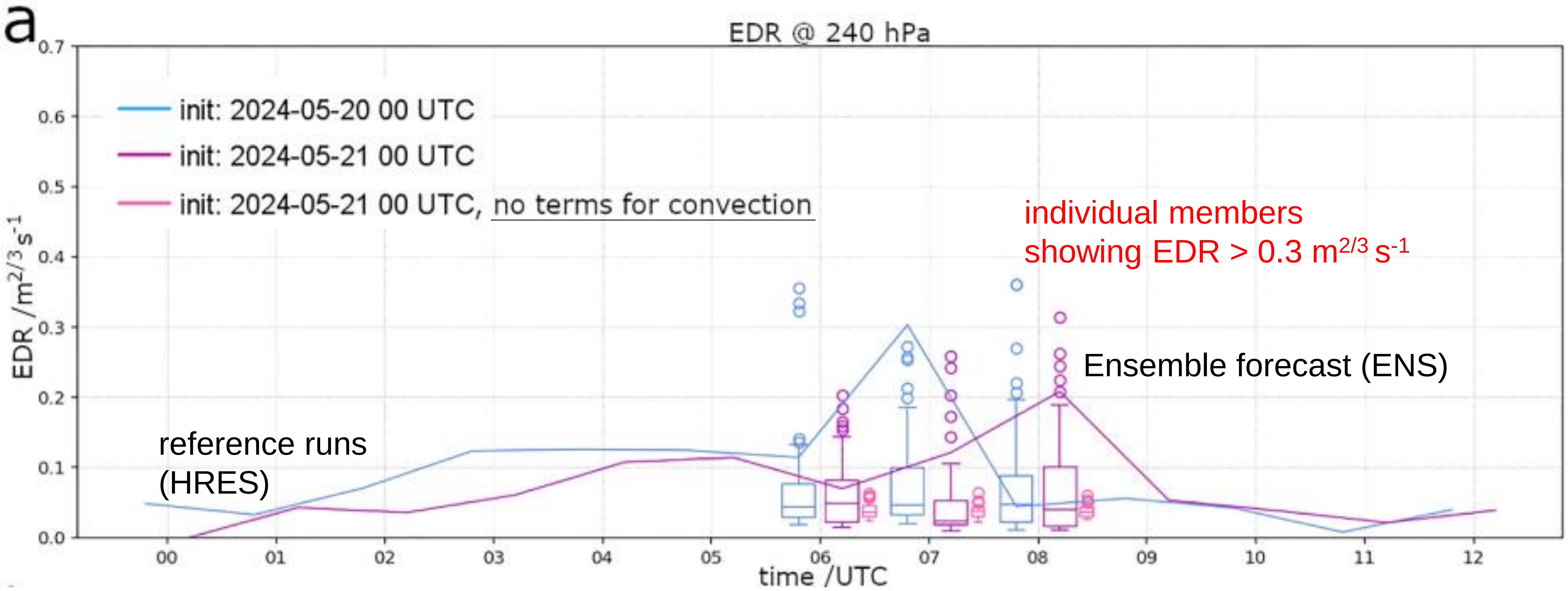
EDR timeseries at the location of the turbulence encounter shows variability in time



Main contributions to ECMWF EDR index by the terms for convection for this event



Main contributions to ECMWF EDR index by the terms for convection for this event



vertical diffusion scheme + convective momentum transport + convective gravity wave drag

must be taken into account

Summary

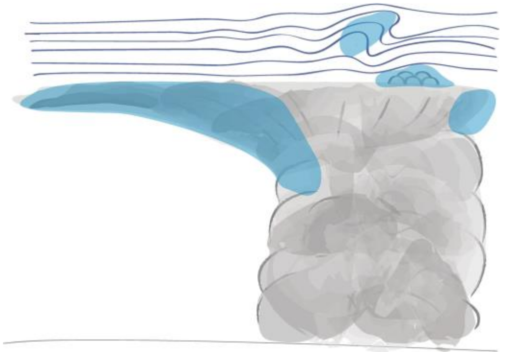
- turbulence encounter by SQ321 was caused by **convection**
  (study of detailed processes requires convection permitting simulations)

- ECMWF ensemble probability: **10% to 40%** for EDR $> 0.18\ m^{2/3}\ s^{-1}$ over Myanmar with higher values for shorter lead time (8-hr forecast)

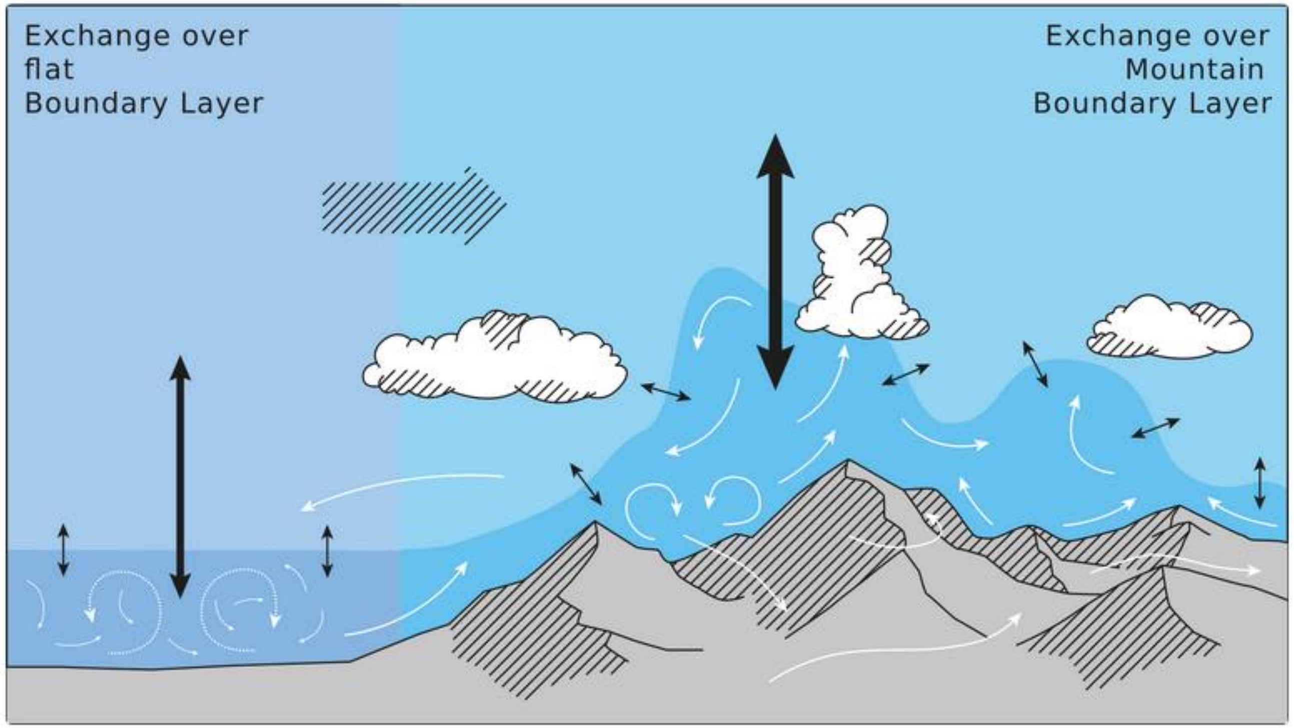
- parameterized **convective momentum transport** and **convective gravity wave drag** give valuable information

- such forecasts could help to **prevent unexpected turbulence encounters** and allow to **take precautions** like switching on the fasten seat belt sign, postponing board service, and request updates by nowcasting services

According to latest forecast, we are expecting an area of turbulence. Passengers and crew please take your seat and fasten your set belts...

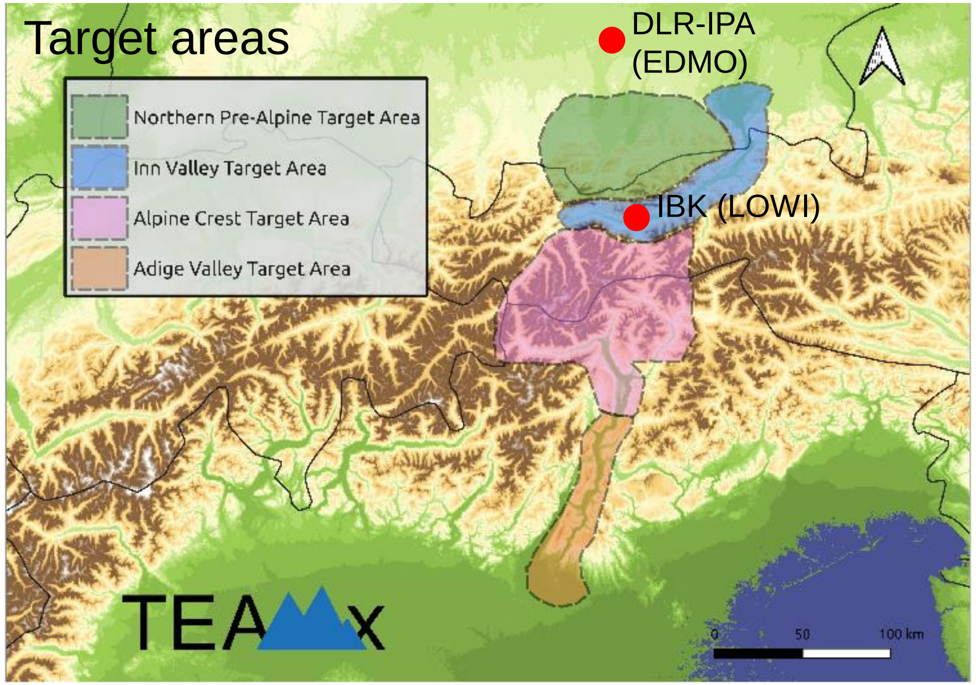


TEAMx: Multi-scale **t**ransport and **e**xchange processes in the **a**tmosphere over **m**ountains – programme and e**x**periment https://www.teamx-programme.org/



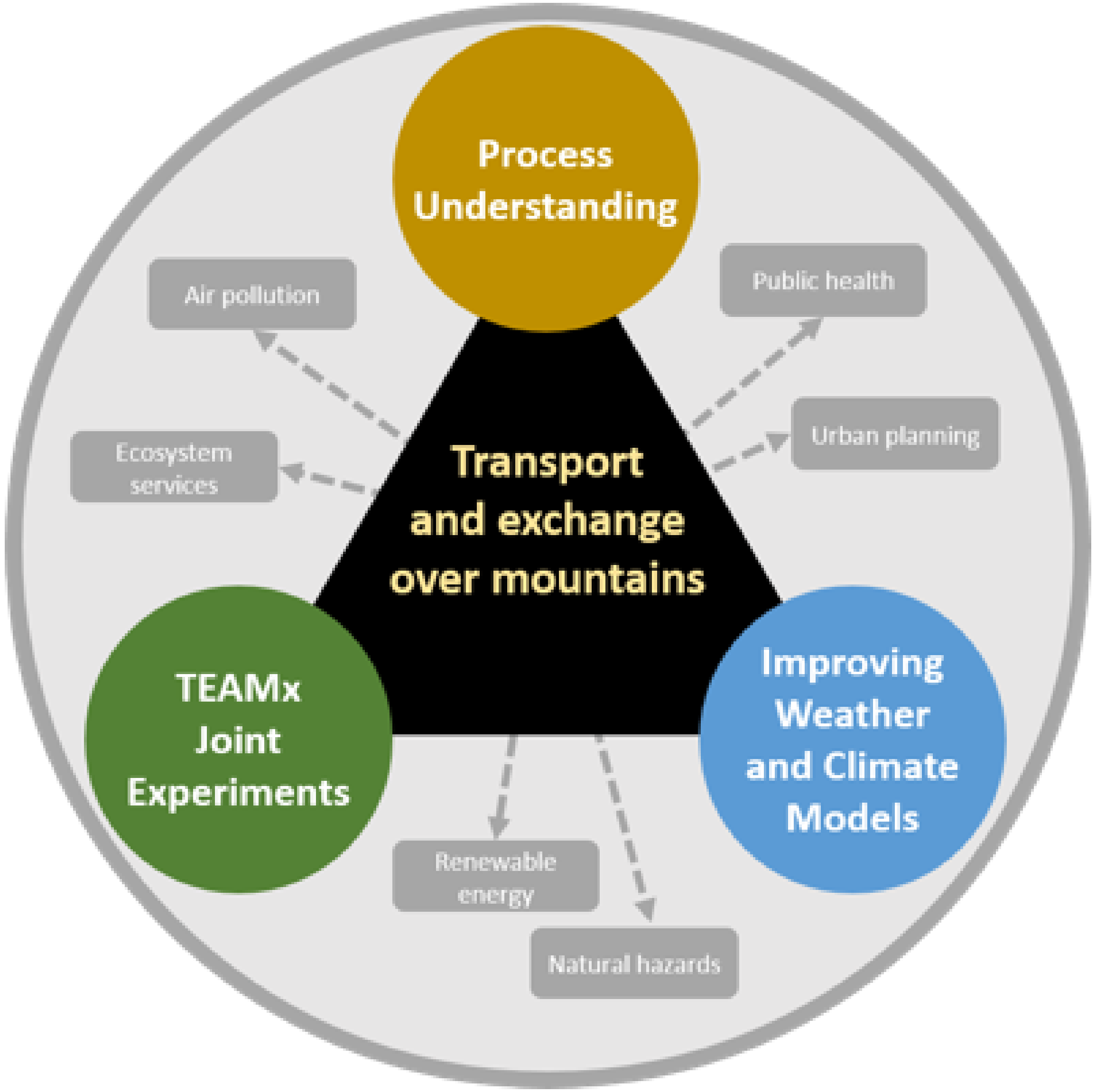
…an international research programme that aims at improving our understanding of exchange processes in the atmosphere over mountains and at evaluating how well these are represented in NWP and climate models.

Modelling activities (incl. Large-Eddy-Simulations) & Observations in the central alps



Observational Campaign: 15th September 2024 to 15th September 2025

TEAMx: Multi-scale **t**ransport and **e**xchange processes in the **a**tmosphere over **m**ountains – programme and e**x**periment https://www.teamx-programme.org/



Topics/Working groups:

- Atmospheric Chemistry
- Mountain Boundary Layer
- Mountain Climate
- Orographic Convection
- Surface-Atmosphere Exchange
- Waves and Dynamics

TEAMx: Multi-scale **t**ransport and **e**xchange processes in the **a**tmosphere over **m**ountains – programme and e**x**periment https://www.teamx-programme.org/

Observational campaign:

- Weather stations
- Flux towers
- Radio soundings
- Temperature-relative humidity-profiler
- Wind profiler
- Radar
- Aerosol profiler
- Air quality stations
- Drones
- Lidar
- aircraft (Braunschweig Cessna, DLR Cessna, UK FAAM)
- collect data available from sailplanes (discussions ongoing)

Nafingalm, precampaign 2024

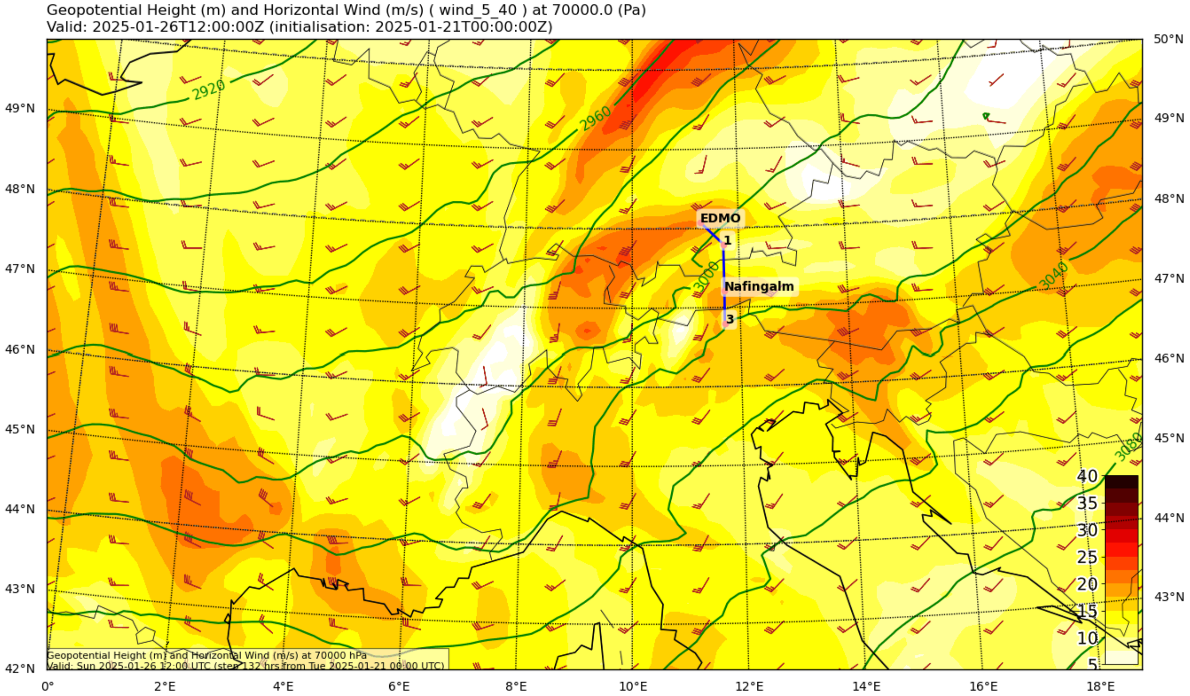
Braunschweig Cessna (test flight Innsbruck Sept 2024)

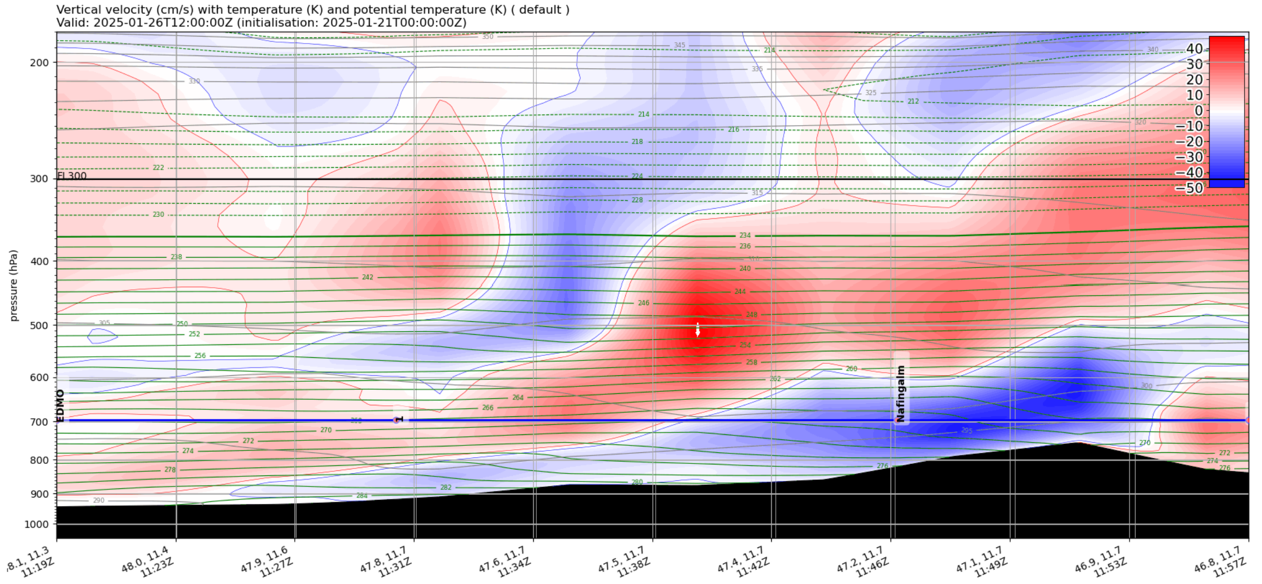
UK sounding team Sterzing, Winter-EOP

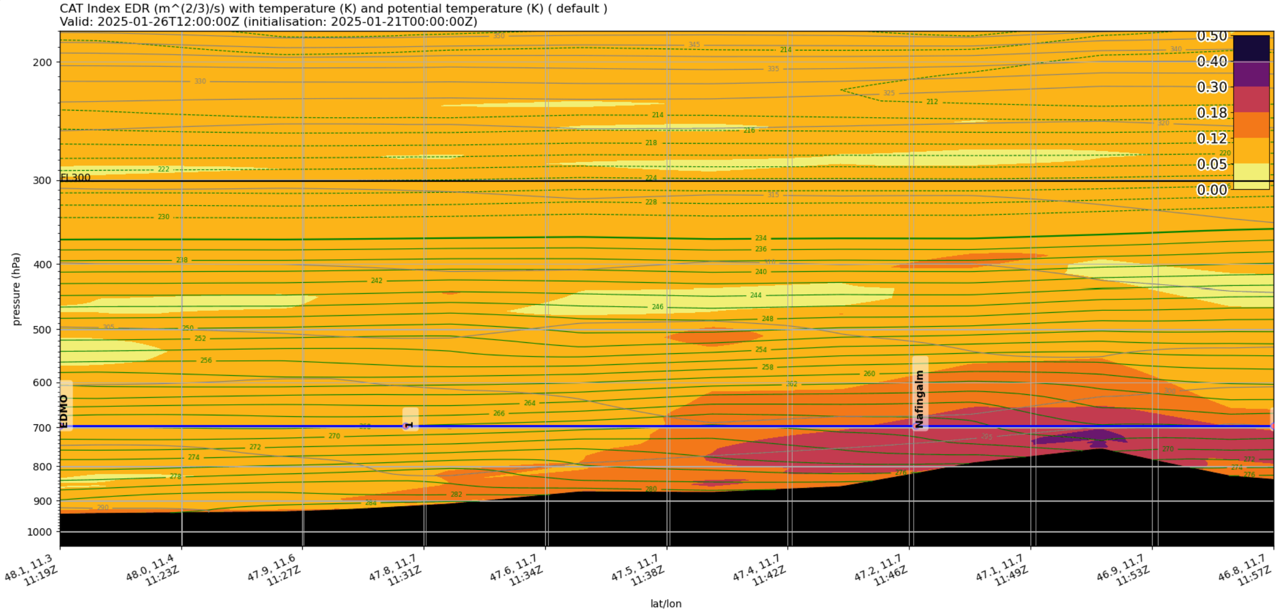
Kolsass, Winter-EOP

TEAMx: ECMWF IFS forecast (9 km horizontal resolution)

wind, vertical velocity, and turbulence/EDR



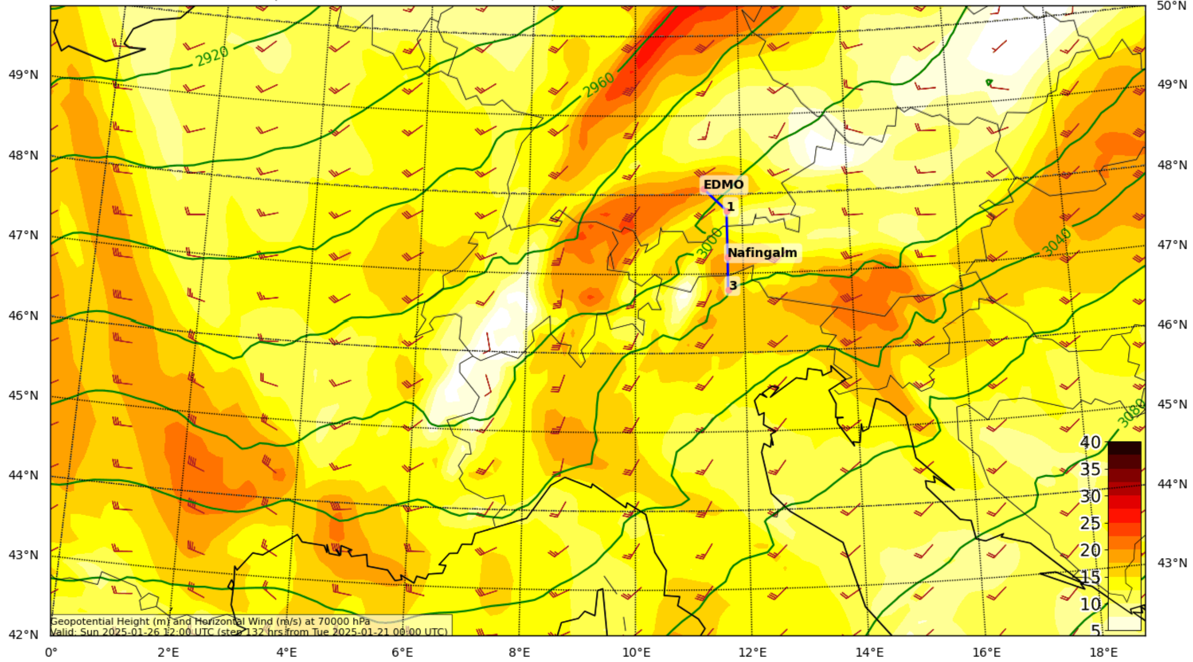




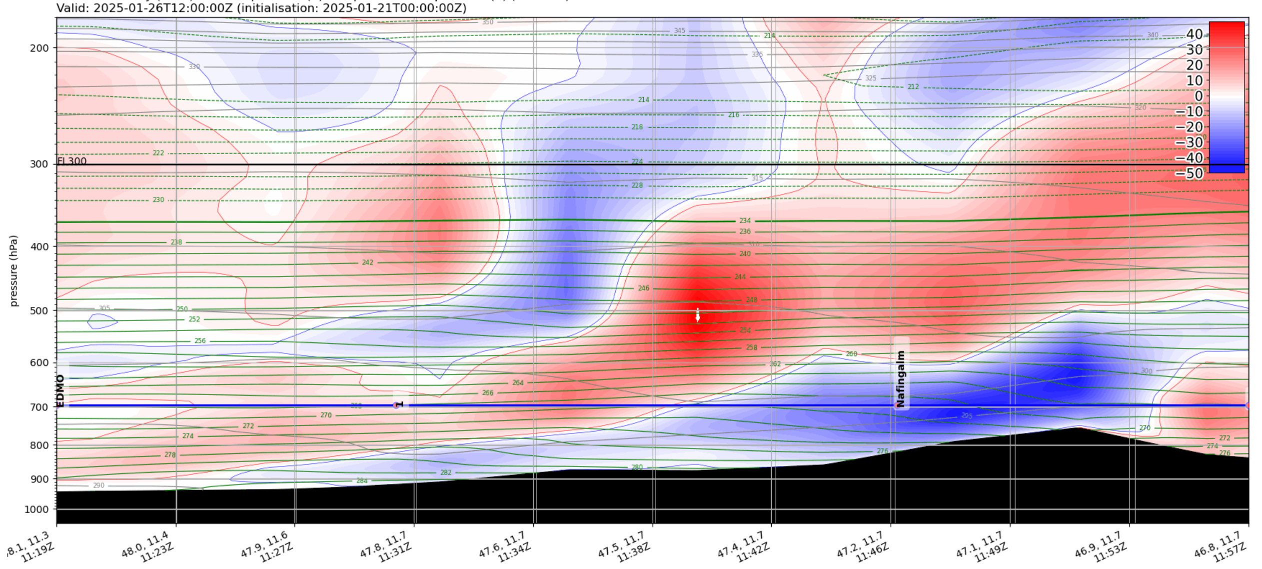
TEAMx: ECMWF IFS forecast (9 km horizontal resolution)

wind, vertical velocity, and turbulence/EDR

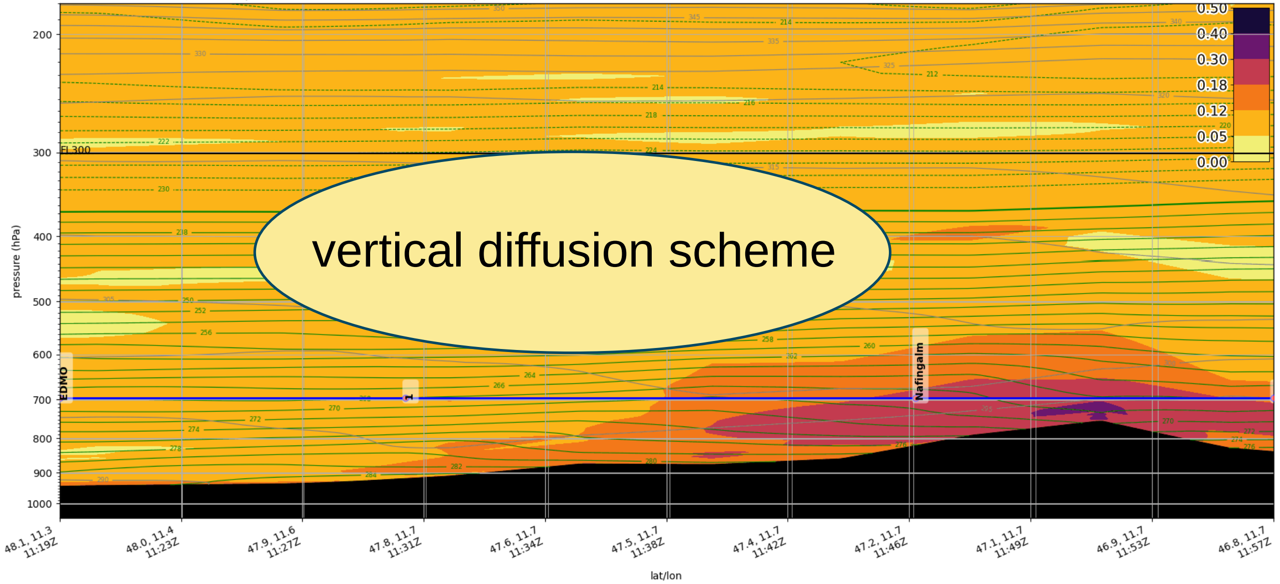
Geopotential Height (m) and Horizontal Wind (m/s) (wind_5_40) at 70000.0 (Pa)
Valid: 2025-01-26T12:00:00Z (initialisation: 2025-01-21T00:00:00Z)

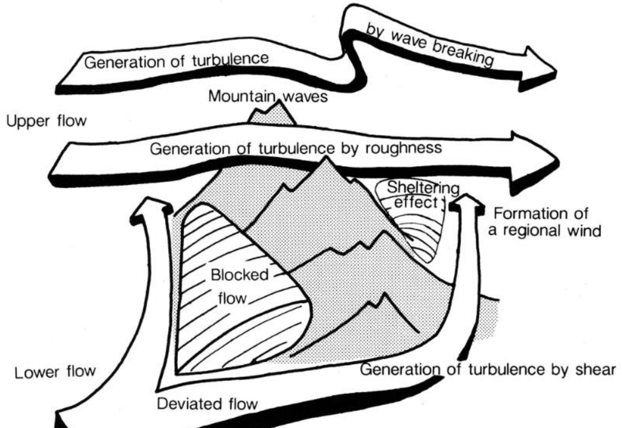


Vertical velocity (cm/s) with temperature (K) and potential temperature (K) (default)
Valid: 2025-01-26T12:00:00Z (initialisation: 2025-01-21T00:00:00Z)



CAT Index EDR (m^(2/3)/s) with temperature (K) and potential temperature (K) (default)
Valid: 2025-01-26T12:00:00Z (initialisation: 2025-01-21T00:00:00Z)



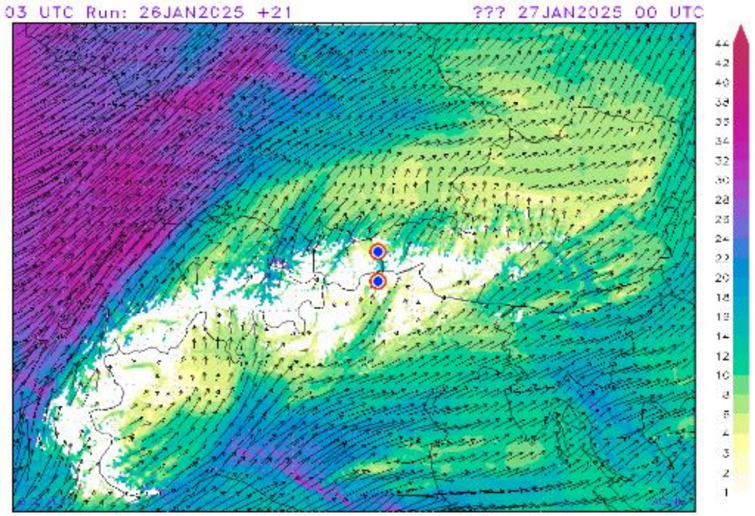


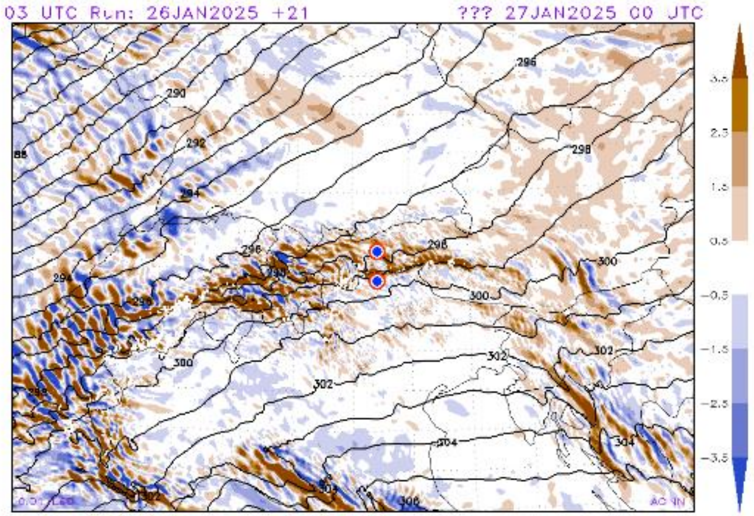
Bougeault et al. 1990

TEAMx: ICON 1-km horizontal resolution forecast

Meteo Swiss ICON 1 km   Mon 27 Jan 00 UTC

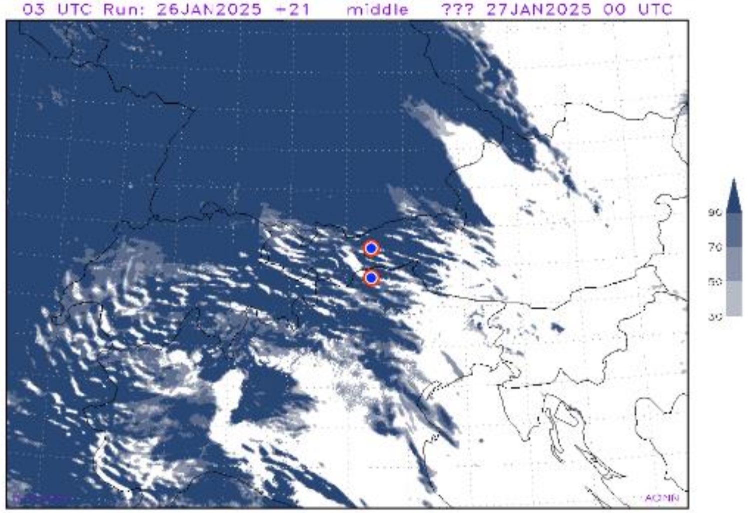
2000 m
Wind
> 10 m/s
South
Foehn north

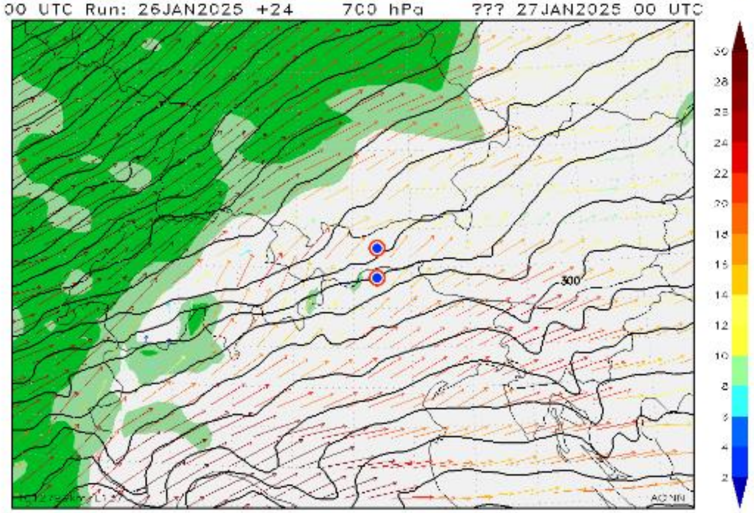




700 hPa
OMEGA,
Z
Mountain
waves
@main crest

Mid level
Cloud Cover
Wave
patterns





700 hPa
Wind, RH
South-
westerlies
16- 18 m/s

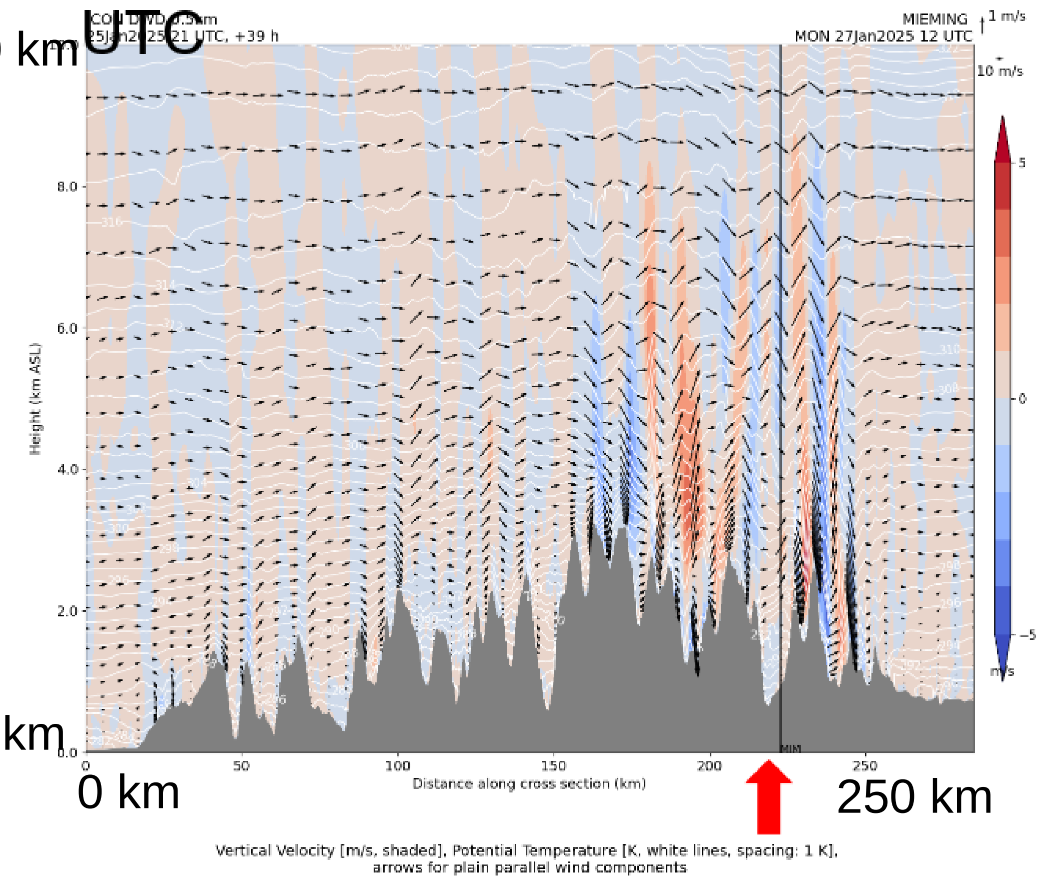
TEAMx: ICON 500m horizontal resolution forecast

DWD ICON 0.5 km

Cross section South – North MIEMING

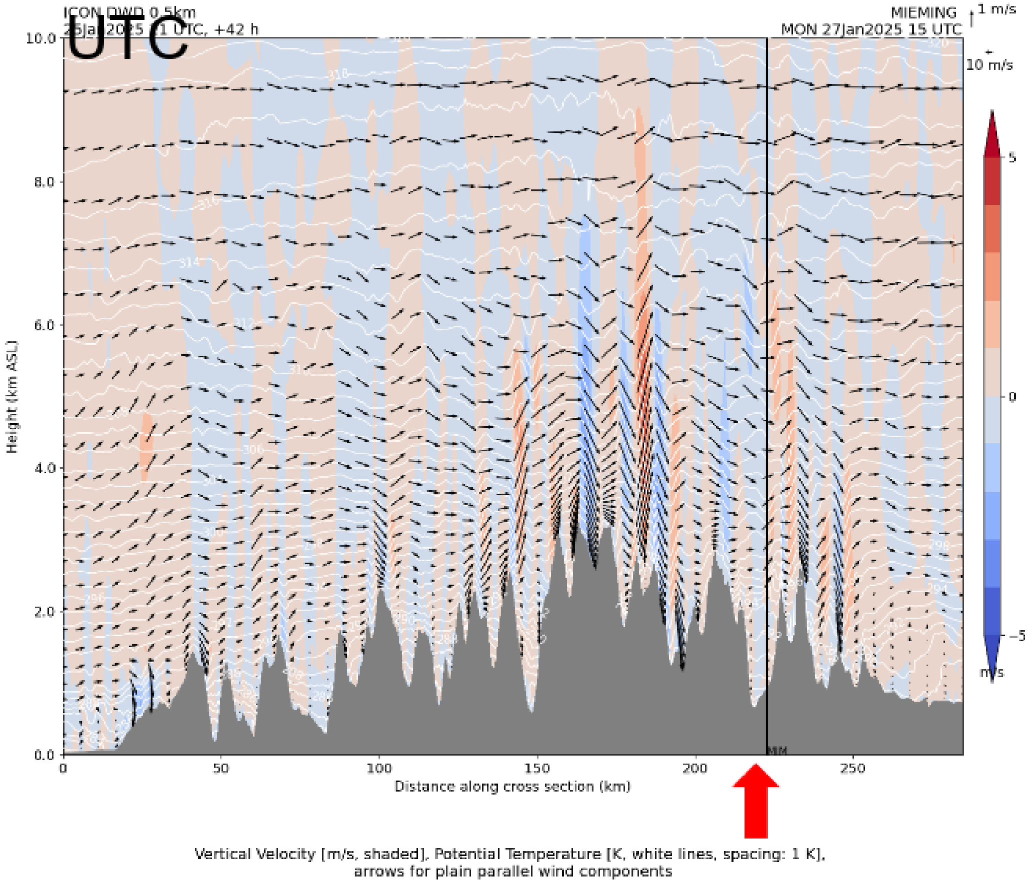
4 – 5 m/s

Mon 27 Jan 12 UTC



3 – 4 m/s

Mon 27 Jan 15 UTC



TEAMx: Current Status winter EOP (6.2.2025)

- Katabatic IOPs: 4 (conditions: Mix of foehn and katabatic; Mix of foehn and gravity flow; perfect katabatic conditions; very good katabatic condition)
- Gravity wave IOPs: 4 (conditions: deep propagating gravity waves; weak shallow waves; weak to moderate waves)

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- Gravity wave IOPs: 4 (conditions: deep propagating gravity waves; weak shallow waves; weak to moderate waves)

TEAMx -Team is looking forward for more interesting IOPs.

ECMWF EDR Index based on total dissipation rate (physical tendencies for horizontal momentum)

vertical diffusion scheme + convective momentum transport + convective gravity wave drag

$$\mathrm{DISS} = \left|\left(u\frac{\partial u}{\partial t}\Big|_{\mathrm{diff}} + v\frac{\partial v}{\partial t}\Big|_{\mathrm{diff}}\right)\right|^{1/3} + \left|\left(u\frac{\partial u}{\partial t}\Big|_{\mathrm{conv}} + v\frac{\partial v}{\partial t}\Big|_{\mathrm{conv}}\right)\right|^{1/3} + \mathrm{GWD},$$

$$\mathrm{GWD} = \left[\left|\left(u\frac{\partial u}{\partial t}\Big|_{\mathrm{gwd}} + v\frac{\partial v}{\partial t}\Big|_{\mathrm{gwd}}\right)\right|\hat{T}_{\mathrm{conv}}\right]^{1/3},$$

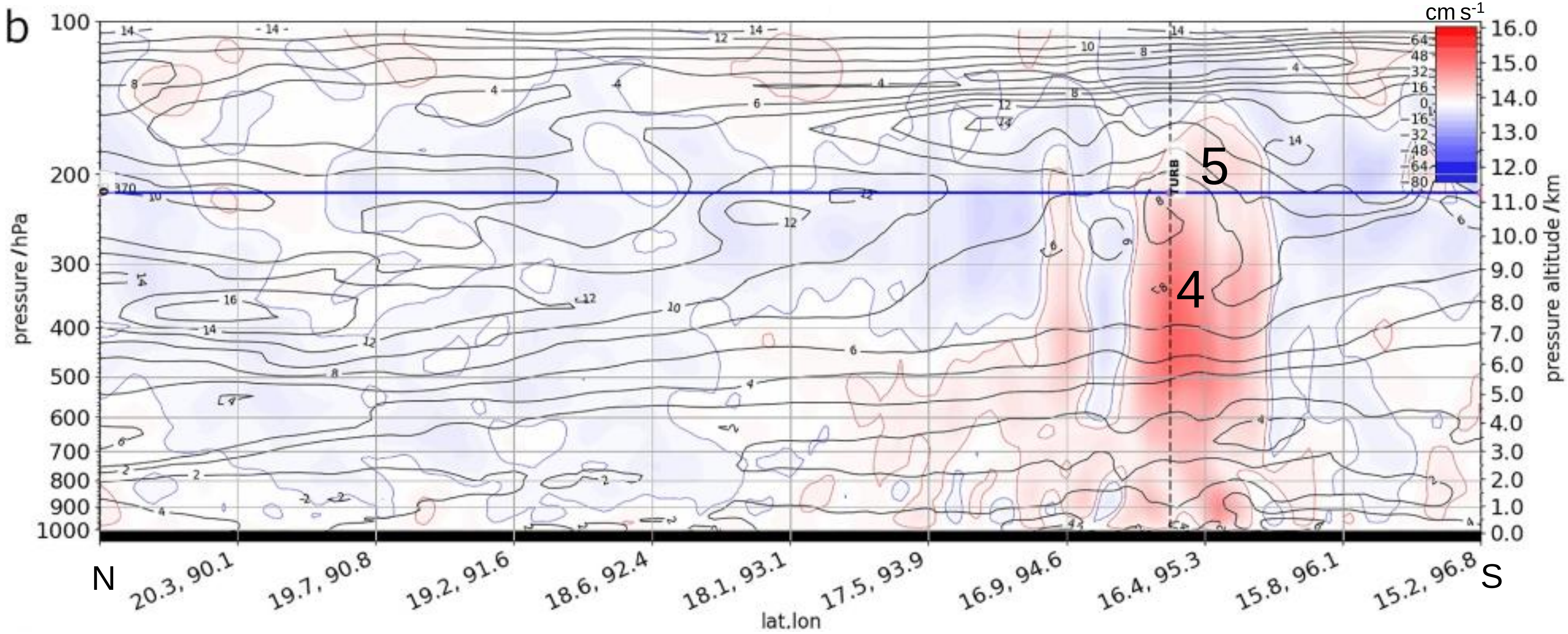
$$\hat{T}_{\mathrm{conv}} = -\frac{c_p}{\hat{T}_0}\int_{p=500hPa}^{top}\frac{\partial T}{\partial t}\Big|_{\mathrm{conv}}\frac{dp}{g}.$$

more details on the parametrizations:
ECMWF. (2023a). IFS documentation CY48R1 - Part IV: Physical processes. IFS Documentation CY48R1(4). https://doi.org/10.21957/02054f0fbf

Gisinger, S., Bramberger, M., Dörnbrack, A., & Bechtold, P. (2024). Severe convectively induced turbulence hitting a passenger aircraft and its forecast by the ECMWF IFS model. *Geophysical Research Letters*, 51, e2024GL113037. https://doi.org/10.1029/2024GL113037

Reference run (HRES) of vertical velocity shows convective updrafts over land

init: 20 May 2024 00 UTC **valid:** 21 May 2024 07 UTC



4. convective updraft (vertical velocity underestimated in ECMWF IFS)
5. positive vertical shear of horizontal wind (isolines of horizontal wind speed)