B06 Impact of small scale dynamics on UTLS transport and mixing

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Motivation

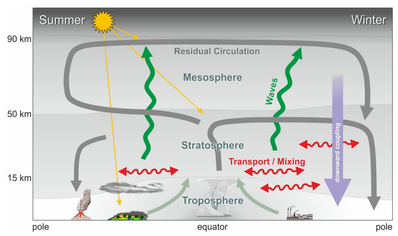


Figure 1: Schematic of transport pathways in the atmosphere between surface and 100 km altitude.

- Transport & mixing in the UTLS depends on motions on a broad range of scales
- Dominant drivers of stratospheric circulation: Rossby waves and gravity waves (GW) along with their Stokes drift
- UTLS composition as a consequence of horizontal and vertical transport processes between surface & mesosphere
- Turbulence leads to mixing
- Parametrisations required to study the effects of the motions on the smallest scales

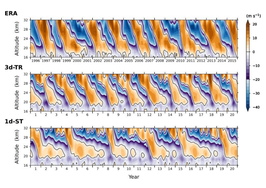


Figure 2: Equatorial QBO in the zonal-mean zonal wind in ERA, ICON/MS-GWaM and ICON with conventional parameterization (Kim et al 2024)

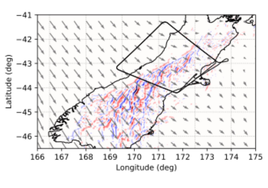


Figure 3: ICON-simulated orographically-induced gravity wave field over New Zealand during the Falcon research flight FF09 on 12 July 2014, as part of the DEEPWAVE field campaign (Siri Jagan and Schmidli, 2025)

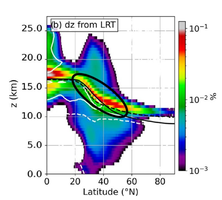


Figure 4: Occurrence frequency of enhanced shear in a tropopause following coordinate system (Kaluza et al., 2021).

GW parametrisations
- no horizontal GW fluxes
- no horizontal GW propagation
- no transient GW-mean-flow interaction
- GW sources not sufficiently dependent on the flow

Turbulence parametrisations
- turbulence parametrisation designed for boundary layer
- source of turbulence are not well represented (jet streams, convection, GWs)
- no interaction between GW and turbulence parametrisation

Process understanding
- effect of shear layers, turbulence and GWs on extratropical tropopause mixing layer
- validation of parametrisation against observations

GW and turbulence parametrisations and their impact on tracer distributions are essential for global studies of the role of the UTLS in climate variability.

Collaborations within TPChange

B03	2TE scheme and ICON on kilometre scale
B07	Coupling of GW and ice clouds
B08	MS-GWaM, 2TE scheme in ICON
B09	MS-GWaM, 2TE scheme in ICON
C03	Water vapour transport representation in models
C09	Impact of GW on tracer transport in the stratosphere
Z03	Synthesis: MS-GWaM and 2 TE scheme integration in ICON

Results from phase I

- **Subgrid-scale GWs**
  (Achatz 2022; Kim et al 2024; Knop et al 2025; Banerjee et al 2025, submitted to JGR)
  - **Theory** of GW parametrisation (MS-GWaM)/**Horizontal GW propagation** in ICON/MS-GWaM (implementation, effect on QBO etc)
  - **Direct effect** of GWs on tracer transport/Effect on tracer mixing by **coupling MS-GWaM to TKE turbulence parametrisation** in ICON

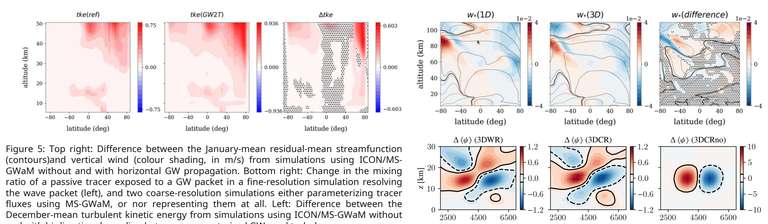


Figure 5: Top right: Difference between the January-mean residual-mean streamfunction (contours)and vertical wind (colour shading, in m/s) from simulations using ICON/MS-GWaM without and with horizontal GW propagation. Bottom right: Change in the mixing ratio of a passive tracer exposed to a GW packet in a fine-resolution simulation resolving the wave packet (left), and two coarse-resolution simulations either parameterizing tracer fluxes using MS-GWaM, or nor representing them at all. Left: Difference between the December-mean turbulent kinetic energy from simulations using ICON/MS-GWaM without and with bi-directional coupling between parameterized GWs and turbulence.

- **Turbulent mixing of tracers**
  (Bašták Ďurán et al. 2020, 2022; Siri Jagan and Schmidli, 2025, subm.)
  - Update of **two-energies turbulence scheme** (2TE scheme). **First adaptation to UTLS** region by introducing a revised turbulence length scale
  - Simulation of **mountain waves** and associated **turbulence** (DEEPWAVE campaign) focusing on the effect of turbulence scheme choice and resolution on the simulated event

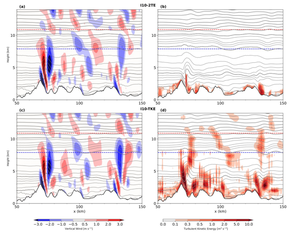


Figure 6: Comparison of simulated mountain wave event along the southern flight leg of FF09 on 2017-07-12 at 18:00 UTC in terms of vertical velocity and parameterized TKE for ICON simulations with new 2TE scheme (top) and operational TKE scheme (bottom).

- **GWs resolved in measurements and models**
  (Umbarkar and Kunkel, 2025)
  - Simulation of **idealized baroclinic life cycles** with ICON focusing on GW, shear and turbulence occurrence in the lowermost stratosphere
  - **Synergistic analysis** of GW, shear, turbulence and tracer mixing in the LMS in a baroclinic wave over the North Atlantic using ICON, IFS, ERA5, and observations

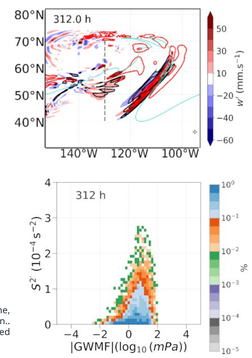


Figure 7, top: Vertical wind (coloured), dynamical tropopause (cyan line, 3.5 PVU), GW momentum flux (black line, log10 (mPa), vertical wind shear of small scales (red line, in 10^{-4} s^{-2}) at 11 km altitude, ICON idealized simulation.. Bottom: Relation of vertical wind shear of small scales and GW momentum flux for Richardson numbers < 5, idealized ICON simulations.

Research plan phase II

Main goal:
Understanding and parametrisation of the impact of small-scale gravity waves, turbulence and their mutual interaction on transport and mixing in the UTLS

Work program

1. Impact of **GWs** (direct & via coupling to turbulence) on **tracer transport and mixing**:
   theory, parametrisation, validation in idealized model

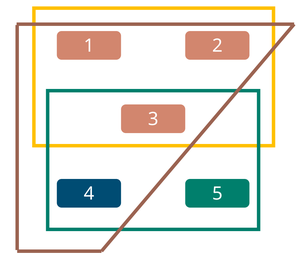
2. Impact of **GWs** (direct & via coupling to turbulence) on **water vapour and ice**:
   theory, validation in idealized model with minimal microphysics

3. **GW impact on turbulence and transport or mixing** of UTLS tracers in the **global atmosphere**:
   ICON/MS-GWaM/2TE (theory & simulations, with GWs from all sources)

4. **Turbulence impact on mixing** of UTLS tracers in the **global atmosphere**:
   ICON/2TE scheme adjustment to UTLS, validation against observations and LES data

5. Role of **UTLS shear in tracer mixing**, including its **connection to GWs**:
   ICON multi-resolution wave permitting, representation in reanalysis data and airborne observations

Internal Collaborations



- MS-GWaM in PinCFlow (1&2)
- MS-GWaM in ICON (1/2 → 3)
- 2 TE scheme – MS-GWaM coupling
- Real case analysis from kilometre to global scales