Karlsruhe Institute of Technology

*Helmholtz Young Investigator Group VH-NG-1243: "**S**ub-seasonal **PRE**dict**A**bility: understanding the role of **D**iabatic **OUT**flow" (SPREADOUT)*

Warm conveyor belts – sensitivities to model uncertainty representation and the role for forecast error growth

Moritz Pickl[1], Simon T. Lang[2], Martin Leutbecher[2], Julian F. Quinting[1] and **Christian M. Grams**[1*]

[1] Institute of Meteorology and Climate Research (IMK-TRO), Karlsruhe Institute of Technology (KIT), Karlsuhe, Germany
[2] European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK
[*] presenting author

(1) Motivation and Research Questions

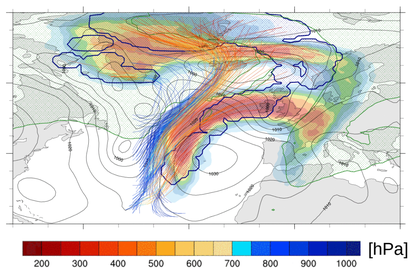
- Warm Conveyor Belts (WCBs) are ascending air streams in extratropical cyclones and involve scale interactions ranging from cloud microphysics to hemispheric Rossby waves
- WCBs modulate the large-scale circulation
- WCBs are hypothesised to amplify model error and introduce uncertainty in numerical weather prediction
- Model error representation schemes such as stochastic physics perturbation (SPPT) introduce error in regions of WCB activity

How do ensemble perturbations affect WCB activity?

What is the role of WCBs in forecast error?

WCB error during **Blocking** onset

tra starting & pmsl 20160309_00 ECMWF analysis & ensemble
tra ending & 2PVU@315K 20160311_00



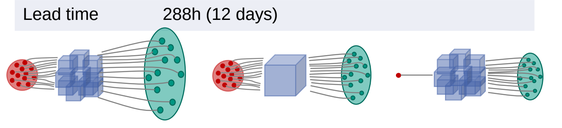
WCB trajectories (blue to red lines coloured in pressure height), WCB outflow (blue hatching), area with PV>2PVU@315K (green hatching), pmsl (black every 5 hPa), and WCB outflow probabilities (shading in 10% interval) during the March 2016 forecast bust. From Grams et al. ,2018.

(2) Data and Methods

Sensitivity Experiments and Operational Ensemble

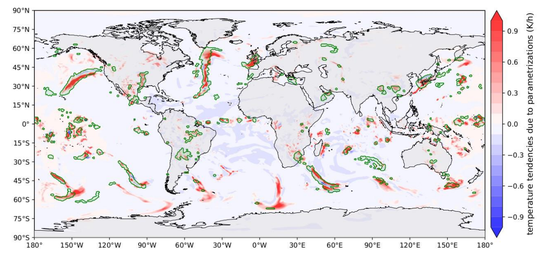
- IFS ensemble experiments: SPPT, IC-Only, SPPT-Only, SPP, SPP_CONV_OFF, SPP_CONV_ONLY, STOCH-DP
- Operational ensemble archived at 1° grid spacing for North Atlantic domain during 2018-present

Model	ECMWF IFS CY46R1
Resolution	TCo399 (~ 36km) with 91 levels
Ensemble size	20 perturbed + 1 unperturbed control member
Simulated period	Aug. 15th - Oct. 15th 2016 ; restarted every other day (32 forecasts; NAWDEX period)
Lead time	288h (12 days)



Lagrangian detection of ascending air streams / WCBs

- 48-h forward trajectories starting on a global equidistant grid below 700 hPa with Lagranto (Sprenger and Wernli, 2015)
- Consider only trajectories ascending at least 600 hPa in 2 days

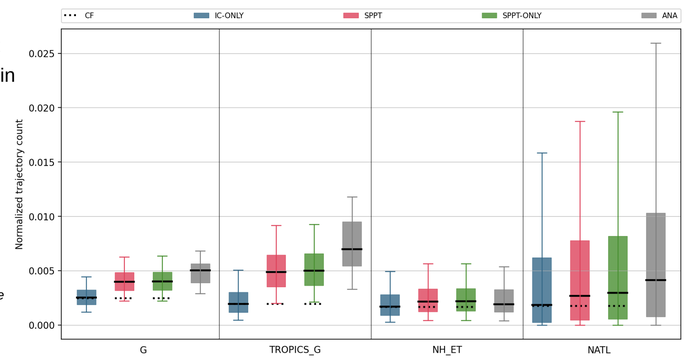


One hour accumulated temperature tendencies due to parametrisations averaged between 700 and 500 hPa from the ERA5 short-term forecast initialised at 1800 UTC on March 8, 2016 at lead time 6 hr (shading) and masks of rapidly ascending air streams in their ascending stage for the same valid time (green contours). Reprinted from Pickl et al., 2022a.

(3) Sensitivities to Model Error Representation

Trajectory Counts

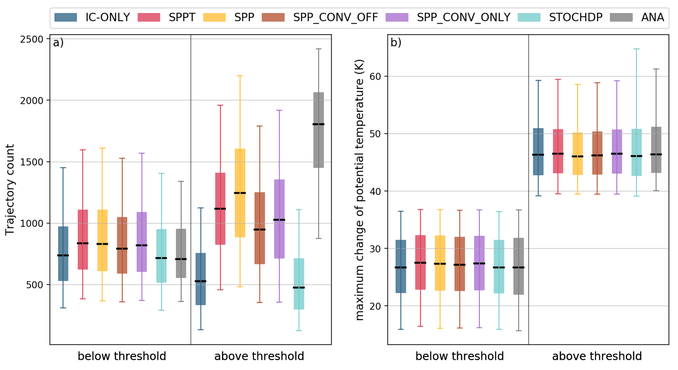
- SPPT systematically increases the trajectory count
- Magnitude is more pronounced in the Tropics than in the Extratropics and scales with the latent heating rate along the trajectories
- IC-perturbations do not affect the counts
- Differences between experiments are independent of lead-time
- Results can be reproduced with operational ensemble using as CF acts as IC-ONLY



Number of trajectories starting globally (G), in the Tropics (TROPICS_G), in the northern hemisphere Extratropics (NH_ET), and in the North Atlantic (NATL), per forecast initialization, member and lead time, normalized by the size of the corresponding region. Reprinted from Pickl et al., 2022a.

Trajectory Characteristics

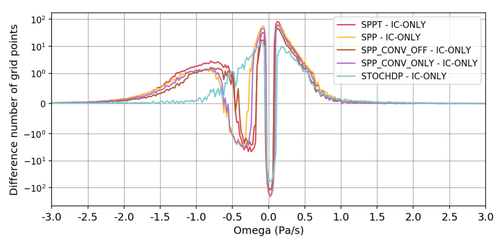
- Increase of the number of strongly heated trajectories with SPPT results from larger effect in the (Sub-) Tropics
- Classifying into weakly and strongly heated trajectories ($\Delta\Theta$>38K) shows that the physical characteristics remain unchanged by stochastic perturbations (SPPT and SPP)
- Convection scheme dominates this effect



(a) Number and (b) diabatic heating rate of trajectories starting globally per forecast initialization, member and lead time, separated into weakly heated ("below") and strongly heated ("above") trajectories by the threshold of 38K. Reprinted from PhD Dissertation of Moritz Pickl, KIT, 2022.

Eulerian Perspective: Vertical Velocities

- Increased occurrence of fast upward motions are balanced by accelerated downward motions
- Stimulation of air parcels that are at rest

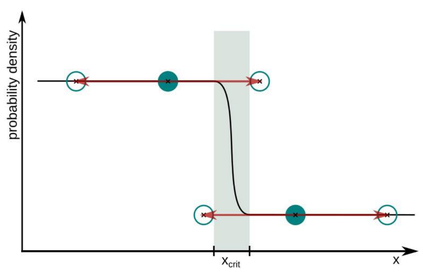


Difference in number of grid points with vertical velocities (omega) at 500hPa in bins of 0.02 Pa/s per forecast, member and lead time between the indicated experiments and IC-ONLY. Reprinted from PhD Dissertation of Moritz Pickl, KIT, 2022.

Stochastic perturbations of physical parametrisations cause unilateral increase in number of ascending air streams without changing their physical properties *(Pickl et al. 2022a, QJRMS)*

Explaining the Unilateral Response

- Positive perturbations are more effective in triggering ascent than negative perturbations in preventing it in a non-linear system characterized by threshold behaviour (for example atmospheric convection)

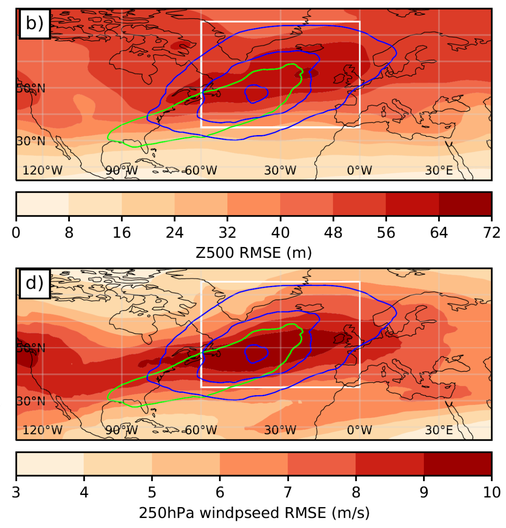


Schematic PDF of a non-linear system (black line) and the effect of symmetric perturbations (red arrows). Reprinted from Pickl et al., 2022a.

(4) Role for Forecast Error

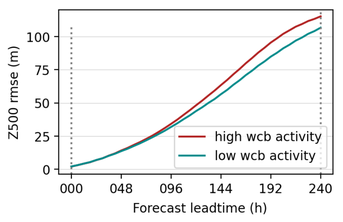
Operational WCB Ensemble Forecast Data

- operational IFS forecasts for DJF 2018/19 19/20 20/21 with ~27000 individual ensemble members, domain see right
- forward trajectories (600hPa / 48h), gridded in **inflow** (p > 800 hPa), **ascent** (800 hPa < p < 400 hPa) and **outflow** (p < 400 hPa)



RMSE and WCB Activity

- mean RMSE over 3 seasons and 0-240h lead time.
- RMSE of 500 hPa Geopotential (Z500) and 250 hPa windspeed co-located with WCB outflow (blue)
- more rapid growth of RMSE during high WCB activity



Left: mean RMSE in North Atlantic domain of Z500 stratified according to forecasts with 20% highest and 20% lowest WCB activity in 0-240h.

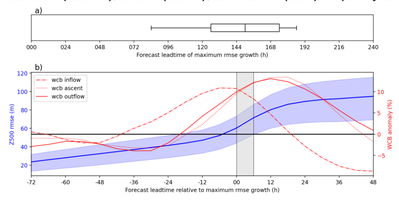
Right: mean RMSE (shading), WCB outflow (blue) and ascent frequencies (green) as contours 5%, 10%, 15%. White box shows North Atlantic domain used for spatial averaging.

Reprinted from Pickl et al., 2022b

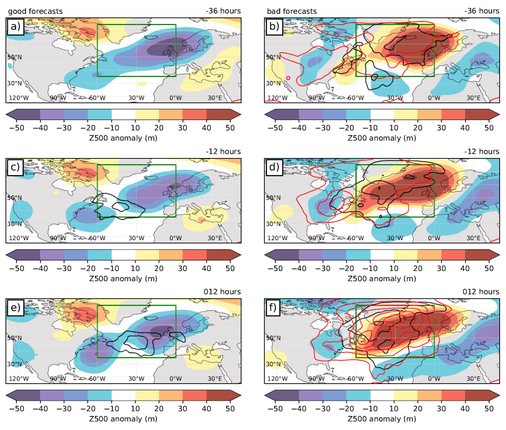
WCB Activity centred on time of Maximum Error Growth

- enhanced WCB inflow precedes time of maximum RMSE growth and is followed by WCB outflow activity reflecting WCB activity centred around time of maximum error growth (+150h)
- long lasting enhanced WCB activity prior to worst (in terms RMSE) and suppressed activity prior to best forecasts (not shown)
- Worst forecasts indicate blocked conditions and incipient RMSE growth with upstream trough followed by enhanced WCB outflow

Below: (b) domain-integrated Z500 RMSE in North Atlantic region (blue, mean and interquartile range), centred on time of max. RMSE growth (grey, and distribution of times indicated in (a)) and relative WCB inflow (dashed), ascent (dotted), and outflow (solid) frequency anomaly. From Pickl et al., 2022b

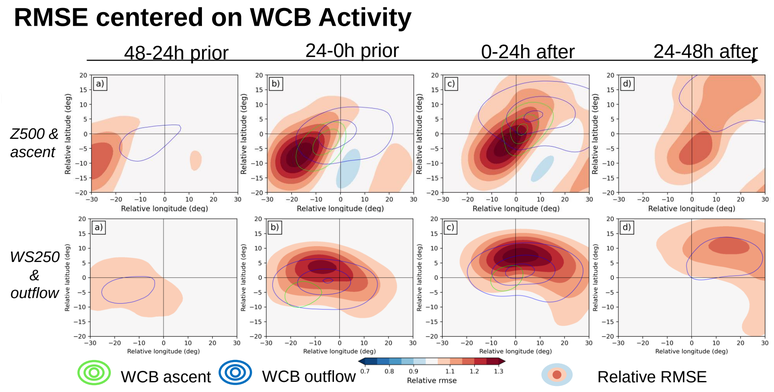


Right: time-lagged composites of Z500 anomaly (shading in m), RMSE anomalies (red contours every 10m) and absolute WCB outflow anomalies (black contours every 2.5%). Separated for 20% best (a,c,e) and 20% worst forecasts (b,d,f) From Pickl et al., 2022b



RMSE centered on WCB Activity

- composites of meteorological fields in 60°x40° lon-lat box spatially centred on centre of mass of WCB ascent and outflow objects and temporally on occurrence of WCB object
- RMSE normalized with local mean
- RMSE in Z500 precedes WCB ascent
- RMSE in upper-level 250 hPa windspeed emerges with and amplifies after WCB outflow occurrence!



Normalized RMSE (shading), WCB outflow and ascent frequencies (blue and green every 12.5%) for RMSE of Z500 (top) centred on WCB ascent objects and RMSE of 250hPa wind speed (bottom) centred on WCB outflow objects. From Pickl et al., 2022b

WCBs amplify and redistribute pre-existing errors rather than being a source of forecast error *(Pickl et al. 2022b, QJRMS)*

(5) Conclusions and Outlook

- SPPT and SPP systematically increase the frequency of rapidly ascending air streams / WCBs without changing their characteristics
- Acceleration of vertical motions
- WCBs and forecast error are climatologically co-located in the North Atlantic
- Coherent spatio-temporal error patterns associated with WCB events
- Process-oriented perspective on model error representation and error growth

Outlook: Implications for precipitation and Rossby wave amplitude

References

Sprenger and Wernli, 2015: The LAGRANTO Lagrangian analysis tool - Version 2.0. *GMD*, doi: 10.5194/gmd-8-2569-2015.

Grams, et al. 2018: An atmospheric dynamics perspective on the amplification and propagation of forecast error in numerical weather prediction models: A case study. *QJRMS*, doi: 10.1002/qj.3353.

Leutbecher et al., 2017: Stochastic representations of model uncertainties at ECMWF: state of the art and future vision. *QJRMS*, doi: 10.1002/qj.3094.

Pickl et al., 2022a: The effect of stochastically perturbed parametrisation tendencies (SPPT) on rapdily ascending air streams. *QJRMS*, doi: 10.1002/qj.4257.

Pickl et al., 2022b: Warm conveyor belts: source or amplifier of forecast errors? *submitted to QJRMS*.

Acknowledgments: This project was funded by the Helmholtz Association as part of the Young Investigator Group "SPREADOUT" (grant VH-NG-1243).

Contact: moritz.pickl@kit.edu and grams@kit.edu