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Technical note: Lowermost-stratospheric moist bias in ECMWF IFS model diagnosed from airborne GLORIA observations during winter/spring 2016

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Abstract. Numerical weather forecast systems like the ECMWF IFS (European Centre for Medium-Range Weather Forecasts – Integrated Forecasting System) are known to be affected by a moist bias in the extratropical lowermost stratosphere (LMS) which results in a systematic cold bias there. We use high spatial resolution water vapour measurements by the airborne infrared limb-imager GLORIA (Gimballed Limb Observer for Radiance Imaging of the Atmosphere) during the PGS (POLSTRACC/GW-LCYLCE-II/SALSA) campaign to study the LMS moist bias in ECMWF analyses and 12 h forecasts in the season from January to March 2016. Thereby, we exploit the 2-dimensional observational capabilities of GLORIA, when compared to in situ observations, and the higher vertical and horizontal resolution, when compared to satellite observations. Using GLORIA observations taken during five flights in the polar sub-vortex region around Scandinavia and Greenland, we diagnose a systematic moist bias in the LMS peaking at +50 % at potential vorticity levels of 6 to 10 PVU. In the diagnosed time period, the moist bias reduces at the highest and driest air masses observed, but clearly persists at lower levels until mid-March. Sensitivity experiments with more frequent temporal output, lower horizontal resolution, and higher/lower vertical resolution, show the short-term forecasts to be practically insensitive to these parameters on time scales of < 12 hours. Our results confirm that the diagnosed moist bias is present already in the initial conditions (i.e., the analysis) and thus supports the hypothesis that the cold bias develops as a result of forecast initialisation. The moist bias in the analysis might be explained by a model bias and/or the lack of water vapour observations suitable for assimilation by the model above the tropopause.

1 Introduction

Accurate representation and reanalysis of water vapour in the lowermost stratosphere (LMS) are important prerequisites for numerical weather forecasting and climate simulations. Water vapour mixing ratios in the tropopause region affect the temperature distribution and the location of the thermal tropopause, and hence stratospheric dynamics (Stenke et al., 2008 and references therein). Radiative forcing has been shown to respond sensitively to changes in LMS water vapour mixing ratios (Solomon et al., 2010; Riese et al., 2012). Furthermore, water vapour in the tropopause region controls the formation of high-altitude cirrus clouds and contrails.

Atmospheric general circulation models are known to be affected by a systematic cold bias in the extratropical LMS, which is strongest in the summer hemisphere, but significant also in the winter hemisphere (Gates et al., 1999; Stenke et al. 2008 and references therein). The cold bias is known to be the consequence of a moist bias which results in too strong longwave cooling. State-of-the-art high-resolution numerical weather prediction systems such as the ECMWF IFS (European Centre for Medium-Range Weather Forecasts – Integrated Forecast System) are also affected by this cold bias (Shepherd et al., 2018) at all forecast ranges and at all resolutions. As specific humidity observations are rarely assimilated above the tropopause, accurate observations of water vapour in the LMS with wide coverage and high spatial resolution are required to validate analyses and forecasts and to aid in model development.

Due to a sharp water vapour contrasts present around the tropopause it is known that numerical diffusion (both explicit and implicit) can lead to too strong water vapour "leakage" from the moist troposphere into the dry stratosphere in low resolution model simulations. Mesoscale fine structures such as tropopause folding, intrusions and filamentary structures on horizontal and vertical scales smaller than the model resolution are likely to contribute to the observed moist bias. Consistently, moderate increase in model resolution (up to 60 km in the horizontal and up to 1 km in the vertical at the tropopause) has been shown to reduce the moist bias and consequently the cold bias (Roeckner et al., 2006, Polichtchouk et al., 2019).

Nevertheless, ECMWF forecasts at 9-18 km horizontal resolution and better than 400 m vertical resolution at the tropopause are still affected by the cold bias in the mid-latitude and polar LMS. Since water vapour is not assimilated by ECMWF above the tropopause, it is possible that the cold bias in high resolution forecasts develops as a result of initialisation from too moist analysis in the mid-latitude and polar LMS. Indeed, using CARIBIC (Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container) in situ observations onboard passenger aircraft, Dyroff et al. (2015) found specific humidity in ECMWF analyses and 18 h and 24 h forecasts to be overestimated by typically 100 to 150% in summer and autumn and 50 to 100% in winter and spring. They suggest that the observed moist bias is caused by small-scale stratospheric intrusions which are still unresolved by the model, numerical diffusion of water vapour across the hydropause from the advection scheme and a lacking constraint on humidity in the stratosphere.

Similarly, Shepherd et al. (2018) found that specific humidity in the polar LMS is overestimated in ECMWF analysis when compared to MLS (Microwave Limb Sounder observations). It should be kept in mind that CARIBIC in situ observations analysed by Dyroff et al. (2015) covered years 2005-2012, making the comparison of this specific study to the more recent ECMWF system with better horizontal and vertical resolution difficult. Moreover, MLS observations have a poor vertical resolution of ~ 5 km in the LMS making the exact quantification of the moist bias across the sharp tropopause difficult. Therefore, high vertical and horizontal resolution observations of water vapour across the tropopause are needed to better quantify the moist bias in the ECMWF system.

Airborne remote sensing observations using lidar or infrared limb sounding fill the gap between focused in situ and global satellite observations. They allow to study mesoscale water vapour distributions across the tropopause with high vertical and horizontal resolution (e.g. Flentje et al., 2005; Ungermann et al., 2012; Schäfler et al., 2018; Woiwode et al., 2018). Here, we use observations by the infrared limb imager GLORIA (Gimballed Limb Observer for Radiance Imaging of the Atmosphere) (Friedl-Vallon et al., 2014; Riese et al., 2014) to quantify the LMS moist bias under Arctic winter and spring conditions. In particular, we investigate the development of the moist bias from January to March 2016. For a flight on 26 February 2016, we furthermore discuss moist bias sensitivity in short 12 h forecasts with more frequent temporal output, lower horizontal and higher/lower vertical resolutions. In Section 2, we introduce the data and diagnostics used. The results are presented in Section 3, and our conclusions are summarized in Section 4.

2 Data and Methods

2.1 GLORIA observations in Arctic winter 2015/16

GLORIA is an airborne thermal infrared limb-imaging Fourier transform spectrometer (Friedl-Vallon et al., 2014). It was deployed onboard the German High Altitude and Long Range Research Aircraft (HALO) during the combined PGS (POLSTRACC/GW-LCYCLE II/SALSA) field campaign in the Arctic winter 2015/16 (Oelhaf et al., 2019). The PGS campaign was designated to study the polar stratosphere in a changing climate, the life cycle of gravity waves, and the seasonality of air mass transport and composition in the LMS. Based in Oberpfaffenhofen (Germany) and Kiruna (Sweden), HALO enabled maximum flight distances exceeding ~8000 km and ceiling altitudes exceeding ~14 km.

GLORIA measures infrared spectra in the spectral range from 780 to 1400 cm^{-1} and views to the right hand side of the flight track. From the spectra, vertical profiles of temperature, trace gases, and cloud parameters are retrieved. Here, we use GLORIA observations in the high spectral resolution "chemistry mode" which involves a spectral sampling of 0.0625 cm^{-1} and an associated horizontal sampling of ~3 km. The water vapour data is characterized by a typical vertical resolution of 400-700 m and combined random and systematic errors of typically 10-20 % (Johansson et al., 2018). The errors are expected to cancel out mostly when the data are analysed as ensemble (e.g. in correlation analyses). As analyzed by Johansson et al. (2018), the median difference and the median absolute deviation between GLORIA and FISH (Fast In situ Stratospheric Hygrometer, Zöger et al. 1999; Meyer et al., 2015) in situ water vapour observations in the UT/LMS during PGS are only 0.13 ppmv and ±0.63 ppmv, respectively. From the water vapour profiles derived from the GLORIA observations, 2-dimensional vertical cross sections of water vapour along the HALO flight tracks are constructed.

In the present study, we use GLORIA observations during five Arctic flights. The flights on 12 January 2016, 18 January 2016, and 20 January 2016 provide a robust estimate of the LMS moist bias in mid-winter, since extended 2-dimensional water vapour distributions associated with independent flights and different meteorological scenarios are analysed. The flights on 26 February 2016 and 13 March 2016 allow us to investigate how the moist bias develops in the late winter and early spring. The choice of the shown data was constrained by the dates of the flights, availability of the GLORIA "chemistry mode" data, observations under sufficiently cloud-free conditions, and availability of observations within the LMS in the polar sub-vortex region. In the following, we show 2-dimensional vertical cross-sections of GLORIA water vapour observations along the HALO flight tracks and compare the observations to the ECMWF system.

2.2 ECMWF IFS data

The ECMWF IFS is a global weather forecasting and analysis system (https://www.ecmwf.int/en/research/modelling-and-prediction) based on a semi-Lagrangian hydrostatic formulation. Between 26 June 2013 and 8 March 2016, the high-resolution forecasts and analysis were at T_L1279L137 resolution, corresponding to 16 km in the horizontal and 300-400 m in the vertical at the tropopause. On 8 March 2016, the horizontal resolution was upgraded to 9 km (or T_{Co}1279) (Hólm et al., 2016; Malardel and Wedi, 2016), which was made possible by the introduction of a cubic octahedral grid (Malardel et al., 2016; see also Wedi, 2014). For comparison to GLORIA observations, we use 00 UTC and 12 UTC analysis and hourly output from a 12 h deterministic forecasts in between the analysis cycles.

In particular, we compare the forecasted specific humidity (qv), converted to volume mixing ratio (parts per million by volume, ppmv), with gas-phase water vapour volume mixing ratios derived from the GLORIA observations. The model output is interpolated in space and time to the geolocations of the tangent points of the GLORIA limb observations. In this manner, vertical cross sections of IFS water vapour corresponding with the vertical cross sections derived from the GLORIA observations are obtained. For vertical assignment of comparable air masses during the winter, we use potential vorticity (PV, unit: PVU) interpolated from the IFS in the same way.

We furthermore perform short (< 12 h) sensitivity forecasts with higher frequency of temporal output (450 s instead of 1 h), lower horizontal resolution (T_{Co}319 and T_{Co}639 instead of T_L1279) and higher/lower vertical resolution (198 and 91 levels instead of 137 levels) to investigate whether the moist bias is sensitive to these model changes. These sensitivity forecasts are performed for comparison with the 26 February 2016 flight and have all been initialized from the operational T_L1279L137 analysis.

2.3 Data selection and correlations analysis

The first step in our analysis is the identification of flight sections located in the LMS and inside the polar sub-vortex region. To identify sub-vortex air masses, we analyse vertical cross-sections of water vapour retrieved from the GLORIA observations and interpolated from the IFS in combination with potential vorticity interpolated from the IFS (Fig. 1). Air masses located in

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the sub-vortex LMS are characterized by low humidity and a low tropopause. We use the 2 PVU level as an indicator for the dynamical tropopause.

Using these parameters, the LMS in the sub-vortex region can be clearly identified in the vertical cross sections and the PV maps, as shown in Figures 1a-d for the flight on 12 January 2016. To quantify the bias, we use flight sections with the dynamical tropopause being mostly located below 10 km. Regions characterised by strong horizontal gradients are avoided, since certain features may be forecasted in a realistic way but do not exactly coincide with the observed location, thus inducing an overestimation of differences between forecast and observation (compare Fig 1a-c tropopause fold between 11:00 and 12:00 UTC). The section of the discussed flight used in our analysis is marked by blue dashed arrows in Figures 1a and 1d.

The residuals between the vertical cross sections show the moist bias of the ECMWF IFS data relative to the GLORIA observations. For the flight on 12 January 2016, the LMS moist bias can be clearly identified above the tropopause, in particular in the sub-vortex region after 12 UTC (Fig. 1c). To quantify the moist bias in the sub-vortex region, we correlate IFS specific humidity with specific humidity measured by GLORIA in the selected flight sections (see Fig. 1e). Vertical assignment of the selected sub-vortex data points is done using the IFS PV data. Using this quantity, dynamically similar air masses can be compared during the course of the winter, which is not possible using for example geometric altitude or potential temperature due to diabatic air mass descent. Furthermore, the mean correlation of the selected data points is shown for quantification (Fig. 1e).

3 Results and Discussion

In Figure 1a-c, we present the GLORIA and IFS data corresponding to the flight on 12 January 2016 and their residuals. During this flight, a wide range of sub-vortex air masses characterized by high PV values (Fig. 1d) was accessed from the Alpes to the Arctic Sea after crossing the polar front jet stream. A developed tropopause fold is clearly and consistently identified in both observations and forecast between 11 and 12 UTC (see also Woiwode et al. 2018). North of the tropopause fold, a lower tropopause and a mostly unperturbed LMS is found in the polar sub-vortex region.

In the residual, noticeable differences between observation and ECMWF analyses and forecasts are found (Fig. 1c). In the first flight part before 12 UTC, positive and negative residuals are mostly a consequence of differences inside the tropopause fold and further mesoscale fine-structures. North of the tropopause fold, a relatively homogeneous systematic moist bias is clearly identified. Figure 1e shows the correlation of the selected IFS data with the GLORIA observations. While the whole ensemble of data points (grey) is mostly scattered around the 1:1 line (yellow solid line), the colour-coded data points beyond 12 UTC (see blue arrows in Fig. 1a,d) clearly show the moist bias increasing with PV. The observed average bias slightly exceeds +50 % at levels of 9 to 10 PVU.

Using the same approach, the subsequent flights are analysed in Figure 2. The GLORIA observations of the flight on 18 January 2016 (Fig. 2a) were performed in a partly perturbed sub-vortex region, with structures characterised by lower PV stretching into the air volume observed by GLORIA (Fig. 2b). The correlation of the IFS and GLORIA data shows a systematic moist bias of the IFS data approaching slightly less than +50 % at 8 PVU. The observed decreasing mean bias towards highest PV values is attributed to the structures from outside the sub-vortex region which are not affected by the moist bias. For the flight on 20 January 2016, a systematic moist bias in the IFS data approaching slightly less than +50 % is found at 8 to 10 PVU (Fig. 2d-f).

At the end of the winter, during the flight on 26 February 2016, largely unperturbed sub-vortex air masses were probed by GLORIA from East Canada to West Greenland (Fig. 2g, h). For the correlation analysis, we use the data points characterised by strongest downwelling (dashed blue arrows in Fig. 2g, h). Here, the mean moist bias peaks slightly below +50 % at 6 PVU, stretches down to ~4 PVU, and decreases also towards higher PV values (Fig. 2i). During the first flight of the double flight on 13 March 2019 (see Oelhaf et al., 2019; only first flight used in Fig. 2j-l), again largely unperturbed sub-vortex air was

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probed in early spring. Similar to the previous flight, the average moist bias peaks at 6 to 7 PVU and now clearly declines to zero at about 10 PVU. In all correlation analyses, the average correlation (cyan solid line) is mostly situated close to the 1:1 line around and below the dynamical tropopause.

In Figure 3, an overlay of the mean IFS/GLORIA correlations is shown for all flights except of the flight on 18 January 2016, which is excluded due to the effects of air masses from outside the sub-vortex region (see above). The overlay shows that the moist bias of the IFS data is largest (i.e. slightly exceeds +50 %) on 12 January 2016 and peaks in the highest and driest air masses accessed by the observations. During the subsequent flights, the mean bias systematically declines in the highest/driest air masses observed. In February and March, the mean bias persists and still approaches peak values close to 50 % at observed water vapour mixing ratios of 5-6 ppmv, respectively.

The mean IFS/GLORIA correlations for the 12 h forecast sensitivity experiments for the flight on 26 February 2016 including more frequent temporal output, lower horizontal resolution and higher/lower vertical resolutions are shown in Figure 4. None of the experiments notably affect the resulting mean correlation of the analysed short-term forecasts.

4 Conclusions

The comparison of state-of-the art high-resolution ECMWF analysis and short forecasts with high resolution GLORIA observations clearly shows a systematic moist bias in the ECMWF system peaking at about +50 % at levels of 6 to 10 PVU. The moist bias reduces at the highest and driest levels at 8 to 10 PVU from mid-winter to early spring, but persists until mid-March at lower levels within the LMS. It extends down to altitudes below 8 km in strongly subsided air masses at the end of February. Sensitivity forecasts using more frequent temporal output, lower horizontal resolution and higher/lower vertical resolutions show practically no response of the mean bias to these changes. It is, of course, possible that for longer lead times resolution will have an impact on the moist bias. Moreover, it should be emphasized that all the sensitivity forecasts were started from the same operational analysis. If the analyses were performed at different resolutions, the conclusion might be different. The presented results support the conclusion that the moist bias is already present in ECMWF analysis – during forecast initialisation – and that on short (< 12 h) time scales the bias is unaffected by the forecast resolution.

The moist bias in the ECMWF analysis could be explained by the lack of observational constraint on specific humidity, as water vapour observations are not assimilated above the tropopause. Therefore, the lower stratospheric moist bias in the analysis is dominated by errors in the model allowing water vapour leakages into the lowermost stratosphere. One possibility to minimize the LMS moist bias in the ECMWF system might be the systematic correction of the water vapour fields above the dynamical tropopause. This would, however, require a comprehensive characterisation of the moist bias in the extratropical LMS during the different seasons and a robust identification of the dynamical tropopause, also in dynamically perturbed regions. Thereby, data from further field campaigns like PGS, regular passenger aircraft observations such as CARIBIC, and the SPARC initiative (see https://www.sparc-climate.org/activities/water-vapour/) could be helpful. Another possibility could be the assimilation of future space-borne global water vapour observations (e.g. infrared limb-imaging or lidar) with high spatial resolution in the LMS.

Author contributions

IP and BH conceived the study. WW, AD and IP elaborated the analyses. WW wrote the manuscript, with contributions from all co-authors. SJ, MH, JU and WW processed and analysed the GLORIA data, with further contributions by the GLORIA team from KIT and JÜLICH. FFV and the GLORIA team performed the GLORIA measurements and operations.

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Data availability

The GLORIA observations can be accessed at the HALO database (https://doi.org/10.17616/R39Q0T, HALO consortium, last access: 16 April 2020) and at the KITopen repository (https://doi.org/10.5445/IR/1000086506, last access: 16 April 2020). The IFS data are available via the ECMWF website (https://www.ecmwf.int/, ECMWF, last access: 16 April 2020). Information on SPARC (Stratosphere-troposphere Processes And their Role in Climate) water vapour assessments can be found at the SPARC website (https://www.sparc-climate.org/activities/water-vapour/, last access: 16 April 2020).

Conflicts of interest

The authors declare no conflicts of interests.

References

Dyroff, C., Zahn, A., Christner, E., Forbes, R., Tompkins, A. M., and van Velthoven, P. F. J.: Comparison of ECMWF analysis and forecast humidity data with CARIBIC upper troposphere and lower stratosphere observations, Q. J. Roy. Meteor. Soc., 141, 833–844, https://doi.org/10.1002/qj.2400, 2015.

Flentje, H., Dörnbrack, A., Ehret, G., Fix, A., Kiemle, C., Poberaj, G., and Wirth, M.: Water vapor heterogeneity related to tropopause folds over the North Atlantic revealed by airborne water vapor differential absorption lidar, J. Geophys. Res., 110, D03115, https://doi.org/10.1029/2004JD004957, 2005.

Friedl-Vallon, F., Gulde, T., Hase, F., Kleinert, A., Kulessa, T., Maucher, G., Neubert, T., Olschewski, F., Piesch, C., Preusse, P., Rongen, H., Sartorius, C., Schneider, H., Schönfeld, A., Tan, V., Bayer, N., Blank, J., Dapp, R., Ebersoldt, A., Fischer, H., Graf, F., Guggenmoser, T., Höpfner, M., Kaufmann, M., Kretschmer, E., Latzko, T., Nordmeyer, H., Oelhaf, H., Orphal, J., Riese, M., Schardt, G., Schillings, J., Sha, M. K., Suminska-Ebersoldt, O., and Ungermann, J.: Instrument concept of the imaging Fourier transform spectrometer GLORIA, Atmos. Meas. Tech., 7, 3565-3577, https://doi.org/10.5194/amt-7-3565-2014, 2014.

Gates, W. L., Boyle, J. S., Covey, C., Dease, C. G., Doutriaux,C. M., Drach, R. S., Fiorino, M., Glecker, P. J., Hnilo, J. J., Mar-lais, S. M., Phillips, T. J., Potter, G. L., Santer, B. D., Sperber,K. R., Taylor, K. E., and Williams, D. N.: An overview of the results of the Atmospheric Model Intercomparison Project (AMIPI), B. Am. Meteorol. Soc., 80, 29–55, 1999.

Hólm, E., Forbes, R., Lang, S., Magnusson, L., and Malardel, S.: New model cycle brings higher resolution, ECMWF Newsletter, No. 147, ECMWF, Reading, UK, 14–19, 2016.

Johansson, S., Woiwode, W., Höpfner, M., Friedl-Vallon, F., Kleinert, A., Kretschmer, E., Latzko, T., Orphal, J., Preusse, P., Ungermann, J., Santee, M. L., Jurkat-Witschas, T., Marsing, A., Voigt, C., Giez, A., Krämer, M., Rolf, C., Zahn, A., Engel, A., Sinnhuber, B.-M., and Oelhaf, H.: Airborne limb-imaging measurements of temperature, HNO_3, O_3, $ClONO_2$, H_2O and

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CFC-12 during the Arctic winter 2015/2016: characterization, in situ validation and comparison to Aura/MLS, Atmos. Meas. Tech., 11, 4737–4756, https://doi.org/10.5194/amt-11-4737-2018, 2018.

Malardel, S., and Wedi, N. P.: How does subgrid-scale parametrization influence nonlinear spectral energy fluxes in global NWP models?, J. Geophys. Res.-Atmos., 121, 5395–5410, https://doi.org/10.1002/2015JD023970, 2016.

Malardel, S., Wedi, N., Deconinck, W., Diamantakis, M., Kühnlein, C., Mozdzynski, G., Hamrud, M., and Smolarkiewicz, P.: A new grid for the IFS, ECMWF Newsletter, No. 146, ECMWF, Reading, UK, 23-28, 2016.

Meyer, J., Rolf, C., Schiller, C., Rohs, S., Spelten, N., Afchine, A., Zöger, M., Sitnikov, N., Thornberry, T. D., Rollins, A. W., Bozóki, Z., Tátrai, D., Ebert, V., Kühnreich, B., Mackrodt, P., Möhler, O., Saathoff, H., Rosenlof, K. H., and Krämer, M.: Two decades of water vapor measurements with the FISH fluorescence hygrometer: a review, Atmos. Chem. Phys., 15, 8521–8538, https://doi.org/10.5194/acp-15-8521-2015, 2015.

Oelhaf, H., Sinnhuber, B.-M., Woiwode, W., Bönisch, H., Bozem, H., Engel, A., Fix, A., Friedl-Vallon, F., Grooß, J., Hoor, P., Johansson, S., Jurkat-Witschas, T., Kaufmann, S., Krämer, M., Krause, J., Kretschmer, E., Lörks, D., Marsing, A., Orphal, J., Pfeilsticker, K., Pitts, M., Poole, L., Preusse, P., Rapp, M., Riese, M., Rolf, C., Ungermann, J., Voigt, C., Volk, C.M., Wirth, M., Zahn, A., and Ziereis, H.: Polstracc: Airborne Experiment for Studying the Polar Stratosphere in a Changing Climate with the High Altitude and Long Range Research Aircraft (HALO). Bull. Amer. Meteor. Soc., 100, 2634–2664, https://doi.org/10.1175/BAMS-D-18-0181.1, 2019.

Polichtchouk, I., Stockdale, T., Bechtold, P., Diamantakis, M., Malardel, S., Sandu, I., Vána, F., and Wedi, N.: Control on stratospheric temperature in IFS: resolution and vertical advection, ECMWF Technical Memorandum no 847, doi: 10.21957/cz3t12t7e, 2019.

Riese, M., Ploeger, F., Rap, A., Vogel, B., Konopka, P., Dameris, M., and Forster, P.: Impact of uncertainties in atmospheric mixing on simulated UTLS composition and related radiative effects, J. Geophys. Res., 117, D16305, doi:10.1029/2012JD017751, 2012.

Riese, M., Oelhaf, H., Preusse, P., Blank, J., Ern, M., Friedl-Vallon, F., Fischer, H., Guggenmoser, T., Höpfner, M., Hoor, P., Kaufmann, M., Orphal, J., Plöger, F., Spang, R., Suminska-Ebersoldt, O., Ungermann, J., Vogel, B., and Woiwode, W.: Gimballed Limb Observer for Radiance Imaging of the Atmosphere (GLORIA) scientific objectives, Atmos. Meas. Tech., 7, 1915–1928, https://doi.org/10.5194/amt-7-1915-2014, 2014.

Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kornblueh, L., Manzini, E., Schlese, U., and Schulzweida, U.: Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model, J. Climate, 19, 3771–3791, https://doi.org/10.1175/jcli3824.1, 2006.

Schäfler, A., Craig, G., Wernli, H., Arbogast, P., Doyle, J.D., McTaggart-Cowan, R., Methven, J., Rivière, G., Ament, F., Boettcher, M., Bramberger, M., Cazenave, Q., Cotton, R., Crewell, S., Delanoë, J., Dörnbrack, A., Ehrlich, A., Ewald, F., Fix, A., Grams, C.M., Gray, S.L., Grob, H., Groß, S., Hagen, M., Harvey, B., Hirsch, L., Jacob, M., Kölling, T., Konow, H., Lemmerz, C., Lux, O., Magnusson, L., Mayer, B., Mech, M., Moore, R., Pelon, J., Quinting, J., Rahm, S., Rapp, M., Rautenhaus, M., Reitebuch, O., Reynolds, C.A., Sodemann, H., Spengler, T., Vaughan, G., Wendisch, M., Wirth, M., Witschas, B., Wolf, K., and Zinner, T.: The North Atlantic Waveguide and Downstream Impact Experiment. Bull. Amer. Meteor. Soc., 99, 1607–1637, https://doi.org/10.1175/BAMS-D-17-0003.1, 2018.

Shepherd, T. G., Polichtchouk, I., Hogan, R. J., Simmons, A. J. Report on Stratosphere Task Force, ECMWF Technical Memorandum no 824,doi: 10.21957/0vkp0t1xx, 2018.

Solomon, S., Rosenlof, K. H., Portmann, R. W., Daniel, J. S., Davis, S. M., Sanford, T. J., and Plattner, G.-K.: Contributions of Stratospheric Water Vapor to Decadal Changes in the Rate of Global Warming, Science, 327, 1219–1223, 2010.

https://doi.org/10.5194/acp-2020-367
Preprint. Discussion started: 25 May 2020

Stenke, A., Grewe, V., and Ponater, M.: Lagrangian transport of water vapour and cloud water in the ECHAM4 GCM and its impact on the cold bias, Clim. Dynam., 31, 491–506, doi:10.1007/s00382-007-0347-5, 2008.

Ungermann, J., Kalicinsky, C., Olschewski, F., Knieling, P., Hoffmann, L., Blank, J., Woiwode, W., Oelhaf, H., Hösen, E., Volk, C. M., Ulanovsky, A., Ravegnani, F., Weigel, K., Stroh, F., and Riese, M.: CRISTA-NF measurements with unprecedented vertical resolution during the RECONCILE aircraft campaign, Atmos. Meas. Tech., 5, 1173–1191, https://doi.org/10.5194/amt-5-1173-2012, 2012.

Wedi, N. P.: Increasing horizontal resolution in numerical weather prediction and climate simulations: illusion or panacea?, Phil. Trans. R. Soc., A372, 20130289.http://dx.doi.org/10.1098/rsta.2013.0289, 2014.

Woiwode, W., Dörnbrack, A., Bramberger, M., Friedl-Vallon, F., Haenel, F., Höpfner, M., Johansson, S., Kretschmer, E., Krisch, I., Latzko, T., Oelhaf, H., Orphal, J., Preusse, P., Sinnhuber, B.-M., and Ungermann, J.: Mesoscale fine structure of a tropopause fold over mountains, Atmos. Chem. Phys., 18, 15643-15667, https://doi.org/10.5194/acp-18-15643-2018, 2018.

Zöger, M., Afchine, A., Eicke, N., Gerhards, M.-T., Klein, E., McKenna, D. S., Mörschel, U., Schmidt, U., Tan, V., Tuitjer, F., Woyke, T., and Schiller, C.: Fast in situ stratospheric hygrometers: A new family of balloon–borne and airborne Lyman alpha photofragment fluorescence hygrometers, J. Geophys. Res.-Atmos., 104, 1807–1816, https://doi.org/10.1029/1998JD100025, 1999.

https://doi.org/10.5194/acp-2020-367
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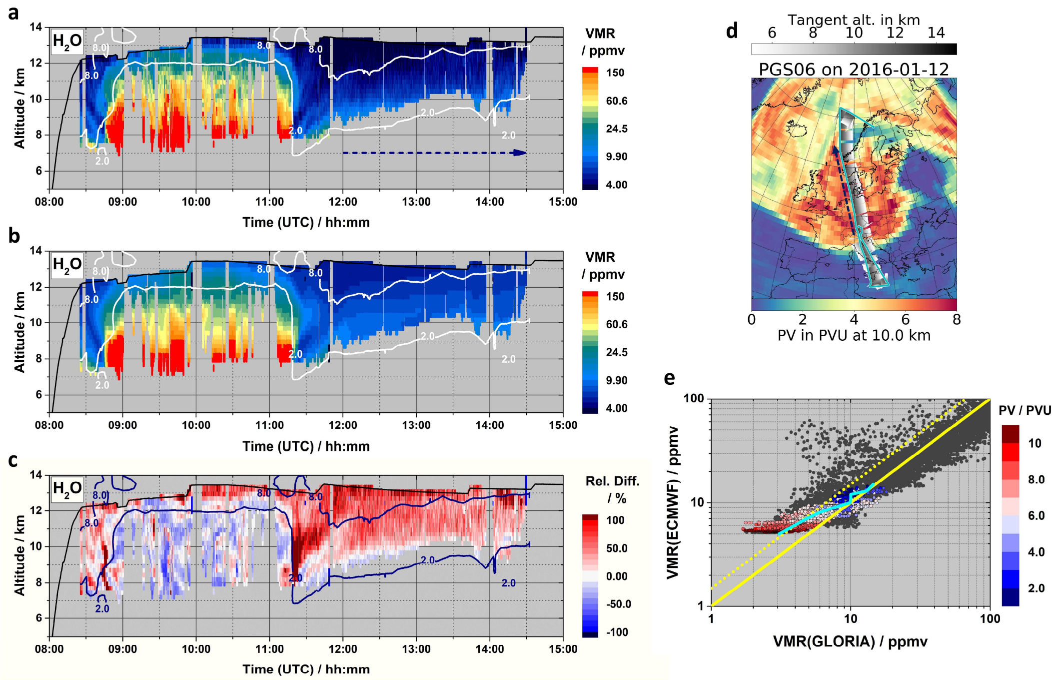

295 **Figure 1:** Principle of LMS moist bias quantification. Vertical cross-section of water vapour during the flight on 12 January 2016 (a) derived from GLORIA observations and (b) forecasted by the IFS. (c) Relative difference of water vapour IFS minus GLORIA. Solid contour lines (white and dark blue, respectively) in (a-c) indicate the PV levels of 2 and 8 PVU. Black solid lines indicate the flight altitude. (d) Flight path of HALO (cyan), tangent points of GLORIA limb observations (grey to white dots) and PV field at 10 km (contour). (e) Correlation between water vapour IFS and GLORIA (grey). Data points selected for the quantification are colour-coded with PV (see flight sections
300 marked by dashed dark blue lines in (a,d)) and average line (cyan). The yellow solid line denotes a 1:1 correlation and the yellow dotted line a bias of +50%. Panels (a,b) modified from Woiwode et al. (2018).

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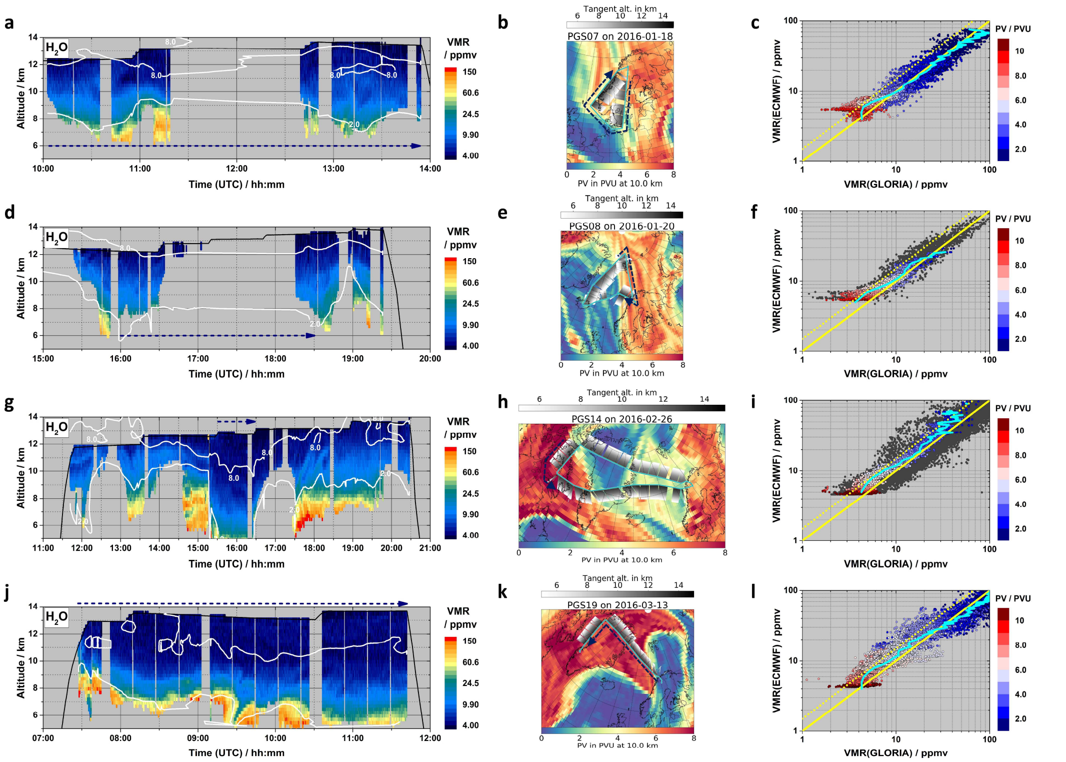

Figure 2: LMS moist bias quantification for selected flights from January to March 2016. GLORIA water vapour (left column),
305 flight path and observation geolocations (middle column), and correlation IFS versus GLORIA (right column) for the flights on 18 January 2016, 20 January 2016, 26 February 2016, and 13 March 2016. For legend see Fig. 1.

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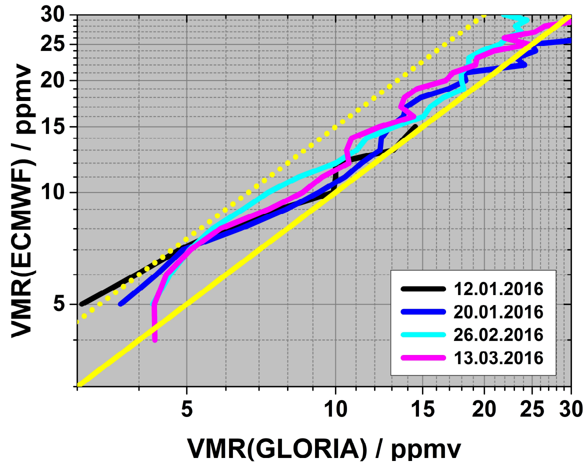

Figure 3: Overlay of mean correlations for flights from January to March 2016 (i.e. cyan lines in Fig. 1e and Fig. 2f,i,l).

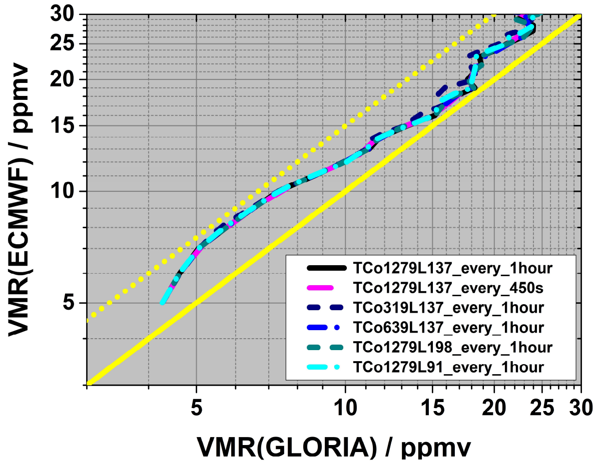

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Figure 4: Low sensitivity of mean correlations between IFS sensitivity forecasts and GLORIA observations during the flight on 26 February 2016. IFS sensitivity forecasts include more frequent temporal output (450 sec (magenta) instead of 1 h (black)), lower horizontal resolution (T_{Co}319 (dark blue) and T_{Co}639 (blue) instead of T_{Co}1279 (black)) and higher/lower vertical resolution (L198 (dark cyan) and L91 (cyan) instead of L137 (black)).