

Evaluation of the boundary layer dynamics of the TM5 model

E. N. Koffi¹, P. Bergamaschi¹, U. Karstens^{2,3}, M. Krol^{4,5,6}, A. Segers⁷, M. Schmidt^{8,11}, I. Levin⁸, A. T. Vermeulen^{9,3}, R. E. Fisher¹⁰, V. Kazan¹¹, H. Klein Baltink¹², D. Lowry¹⁰, G. Manca¹, H. A. J. Meijer¹³, J. Moncrieff¹⁴, S. Pal¹⁵, M. Ramonet¹¹, H.A. Scheeren^{1,13}

1 European Commission Joint Research Centre, Institute for Environment and Sustainability, Ispra (Va), Italy

2 Max-Planck-Institute for Biogeochemistry, Jena, Germany

3 ICOS Carbon Portal, ICOS ERIC at Lund University, Sweden

4 SRON Netherlands Institute for Space Research, Utrecht, Netherlands,

5 Institute for Marine and Atmospheric Research Utrecht, Utrecht, University, Utrecht, Netherlands

6 MAQ, Wageningen University and Research Centre, Wageningen, Netherlands,

7 Netherlands Organisation for Applied Scientific Research (TNO), Utrecht, Netherlands

8 Institut für Umweltphysik, Heidelberg University, Germany

9 Energy research Center Netherlands (ECN), Petten, Netherlands

10 Royal Holloway, University of London (RHUL), Egham, UK

11 Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

12 Royal Netherlands Meteorological Institute (KNMI), Netherlands

13 Centrum voor Isotopen Onderzoek (CIO), Rijksuniversiteit Groningen, Netherlands

14 Atmospheric Chemistry Research Group, University of Bristol, UK

15 Department of Meteorology, Pennsylvania State University, State College, PA, USA

29 February 2016

submitted to Geosci. Model Dev.

Supplementary material

Comparison of IGRA boundary layer heights to ceilometer observations at Cabauw

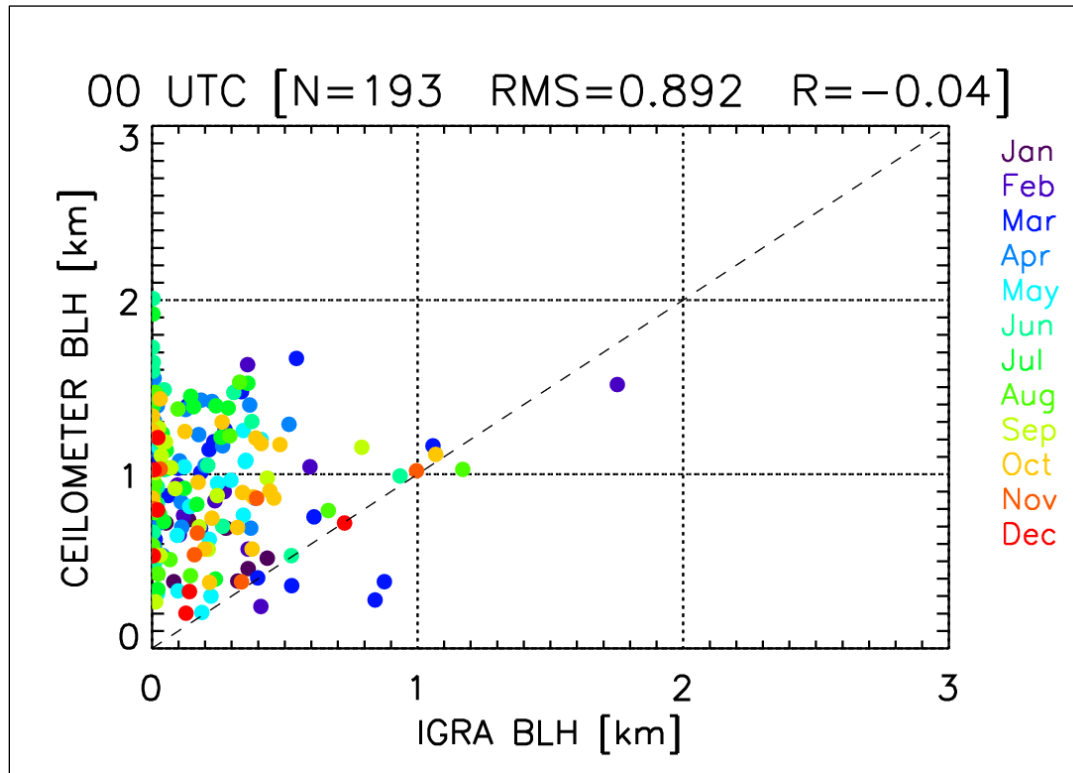


Figure S1: The Cabauw ceilometer boundary layer heights versus IGRA (De Bilt station) data for the year 2010 at 00 UTC are shown. The statistics (RMS in km and correlation coefficient R) are indicated as well as the number of pair of data (N) used to compute these metrics. The different colors indicate the months at which the data were obtained.

Comparison of TM5 boundary layer heights to observations

We extract the BLH in the model both at the location of the InGOS station and at the location of the nearest IGRA station, resulting in a set of four different modeled BLHs labelled by the following acronyms:

- 'TM5': TM5 default version (Eq.1 in Section 3.2 with $R_{ic} = 0.3$); extracted at InGOS stations by using 2D interpolation
- 'TM5_IGRA': As 'TM5', but extracted at IGRA station, which is closest to the selected InGOS station
- 'TM5_INGOS': BLHs computed in TM5 model adopting the InGOS definition of the BLH (i.e., $R_{ic} = 0.25$ and both surface wind and stress velocity are set to zero in Eq.1), extracted at InGOS station. The BLH of the closest model grid point to the selected station is considered.
- 'TM5_INGOS_IGRA': As 'TM5_INGOS', but extracted at IGRA station, which is closest to the selected InGOS station

Furthermore, we evaluate the BLHs as provided by ECMWF analyses and interpolated to TM5 grids (labelled 'ECMWF'). The values of these BLHs are extracted only at the InGOS stations.

For more details see Section 4.1 of the text

We show hereafter only the data for the closest IGRA stations to InGOS ones and for year 2009

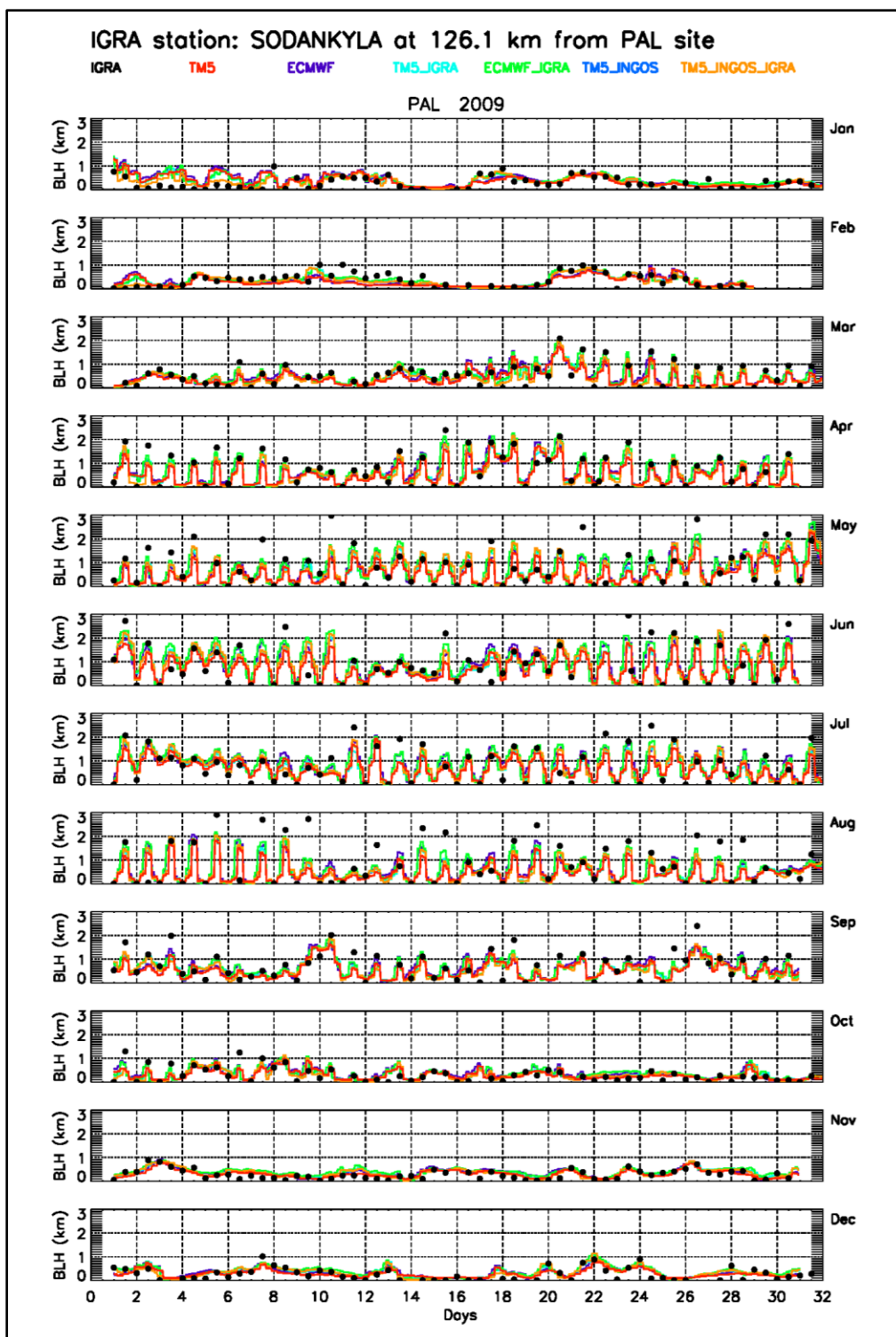


Figure S2: Time series of observed (IGRA in black dot) and modelled (TM5, TM5_IGRA, TM5_INGOS, and TM5_INGOS_IGRA in colors) boundary layer heights relevant for InGOS station Pallas (PAL) are shown. The closest IGRA station to Pallas is Sodankyla. The distance between IGRA and InGOS stations is given of the top of graph. The different model acronyms are defined at page 2 in this document

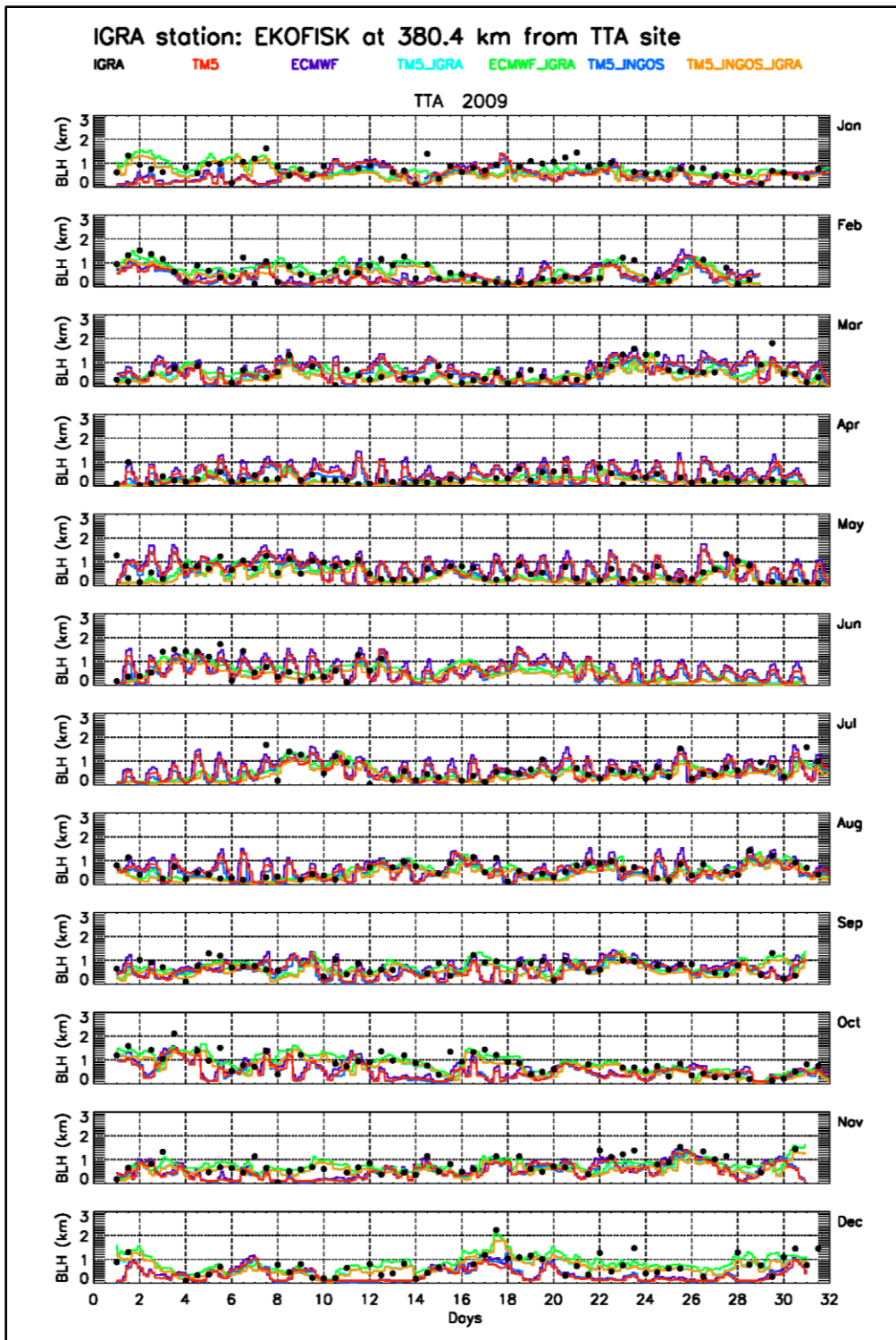


Figure S3: As Figure S2, but for the InGOS station Angus (TTA)

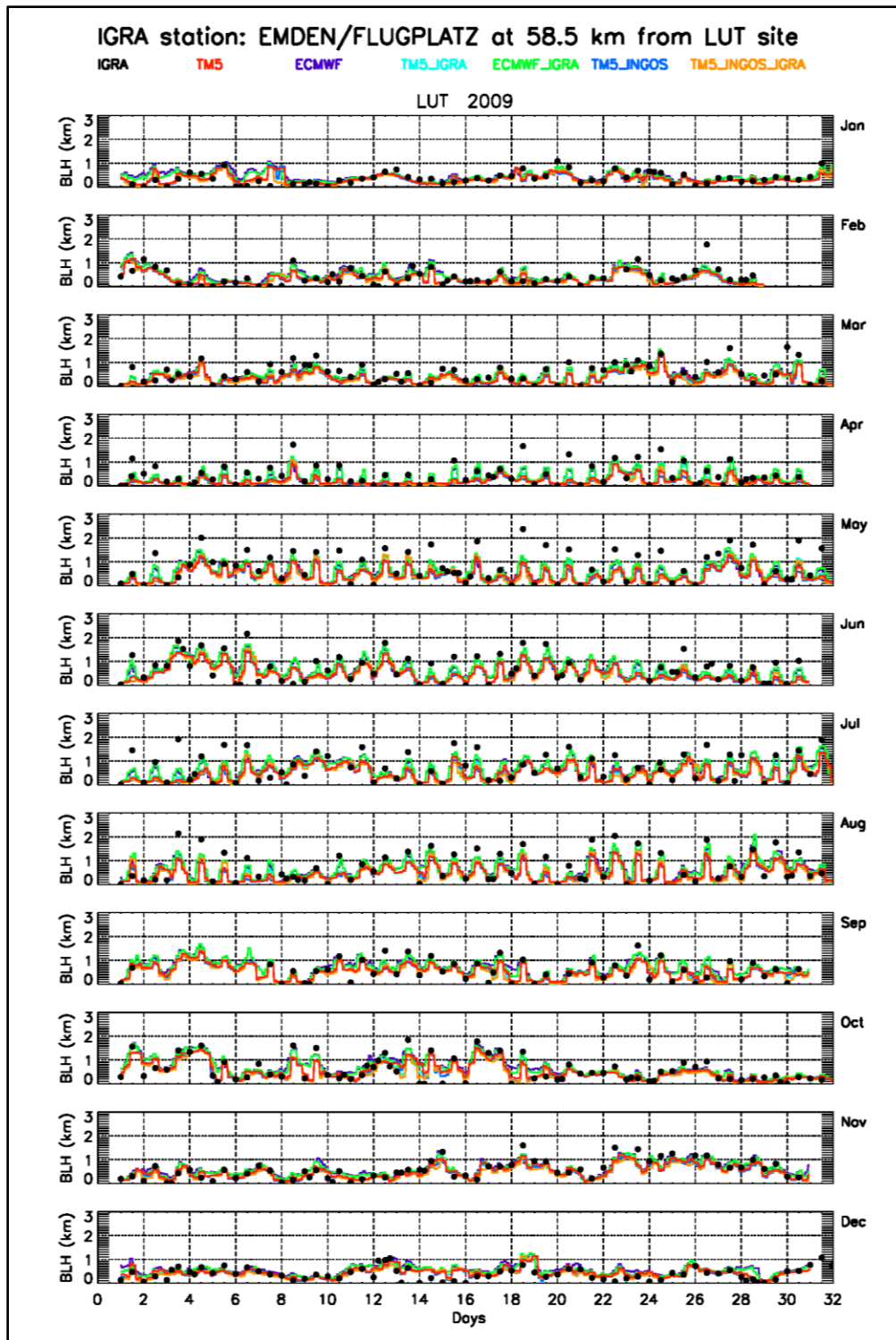


Figure S4: As Figure S2, but of the InGOS station Lutjewad (LUT)

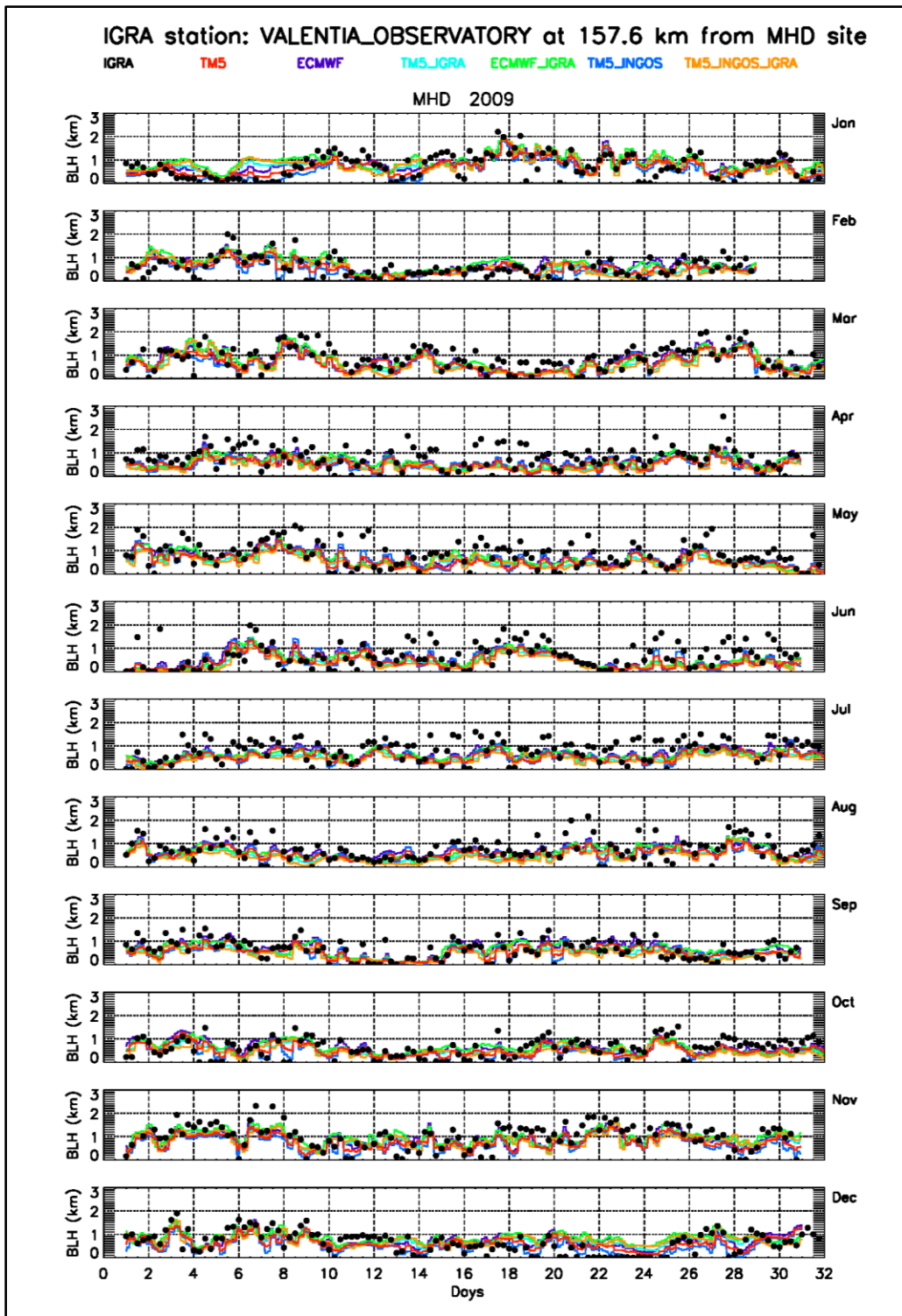


Figure S5: As Figure S2, but for the InGOS station Mace Head (MHD)

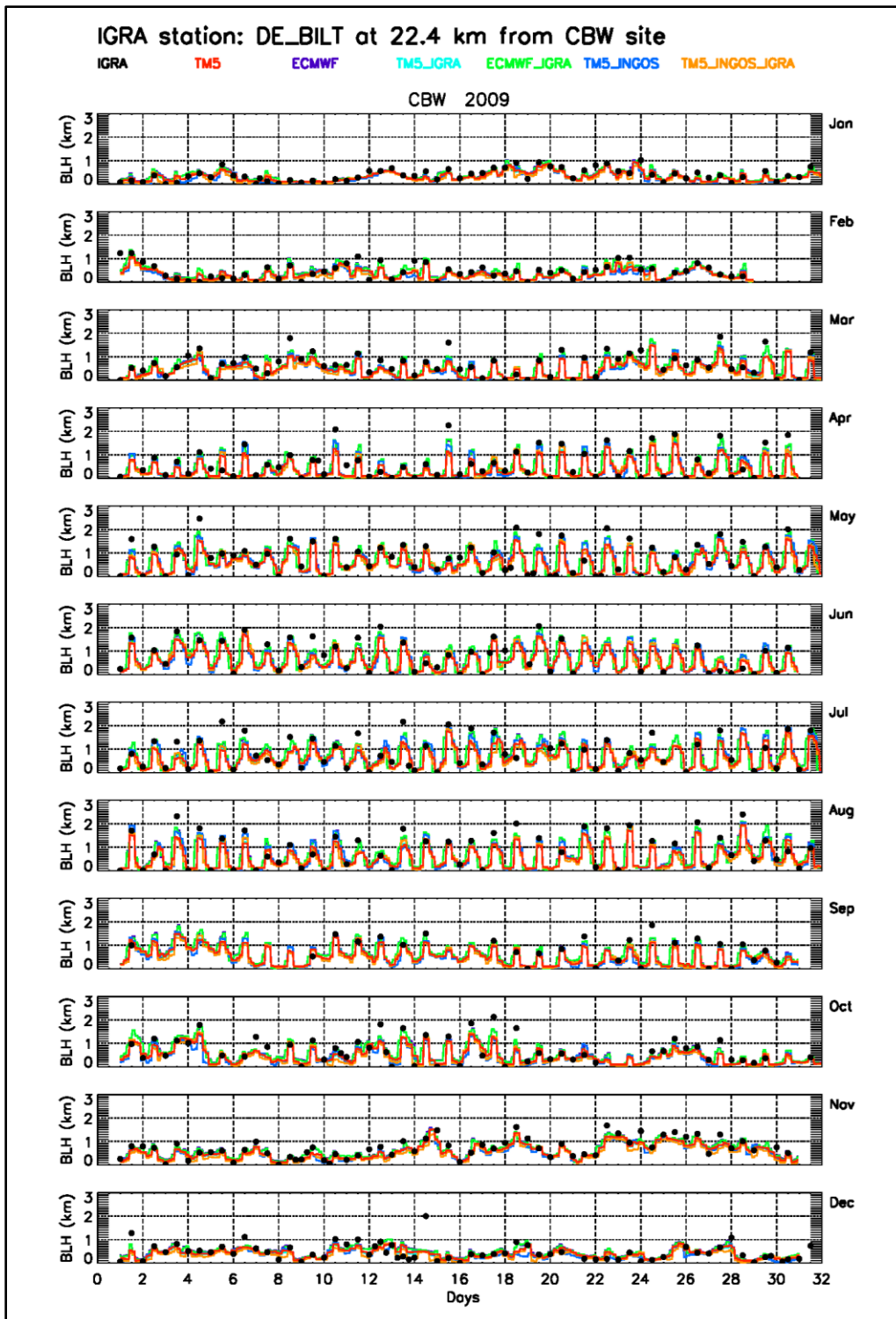


Figure S6: As Figure S2, but for the InGOS station Cabauw (CBW or CB1/CB4)

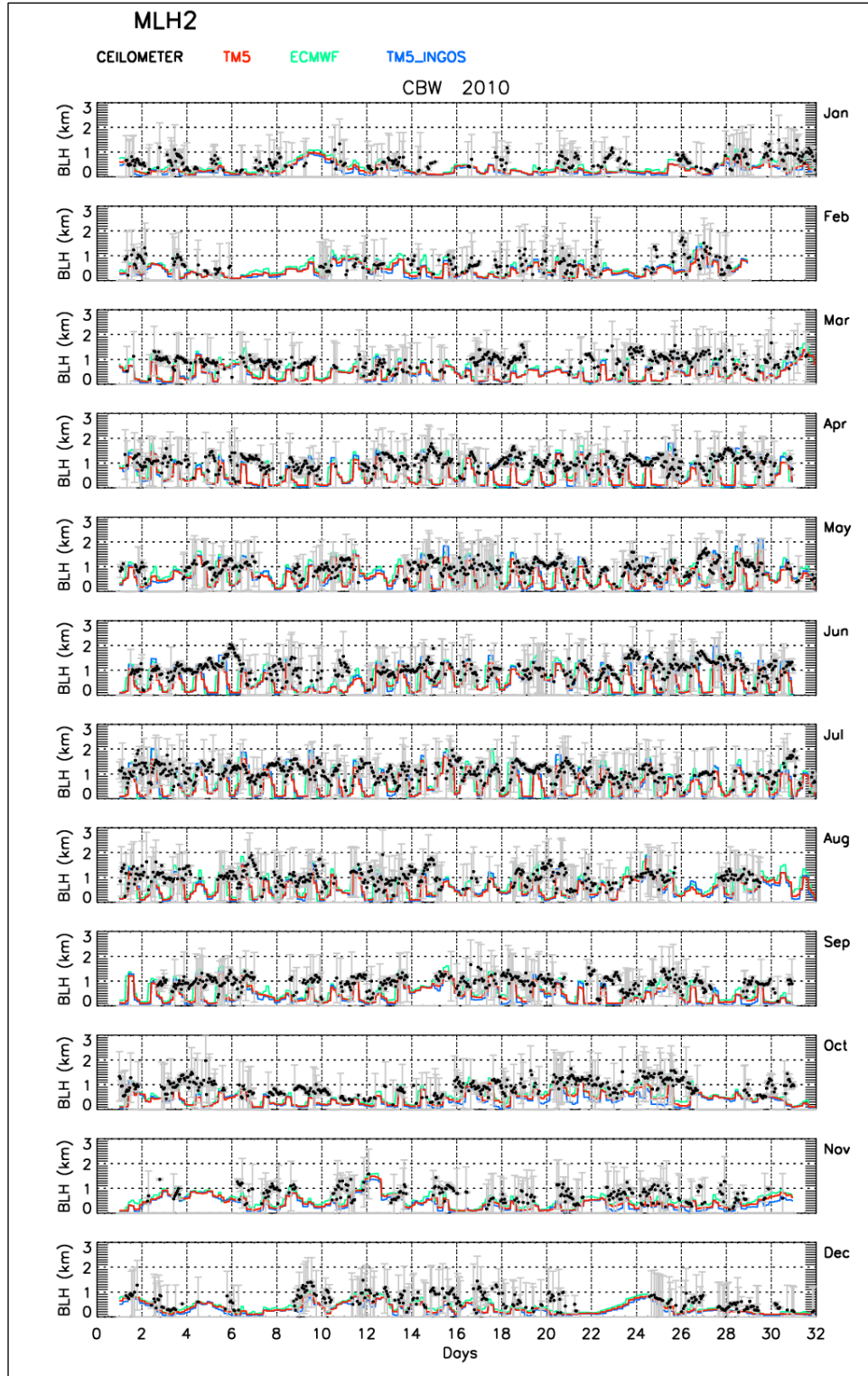


Figure S6b: As for Figure S6, but the observations for the year 2010 are from the ceilometer measurements at Cabauw (CBW). The standard deviations over 1h period are shown in grey

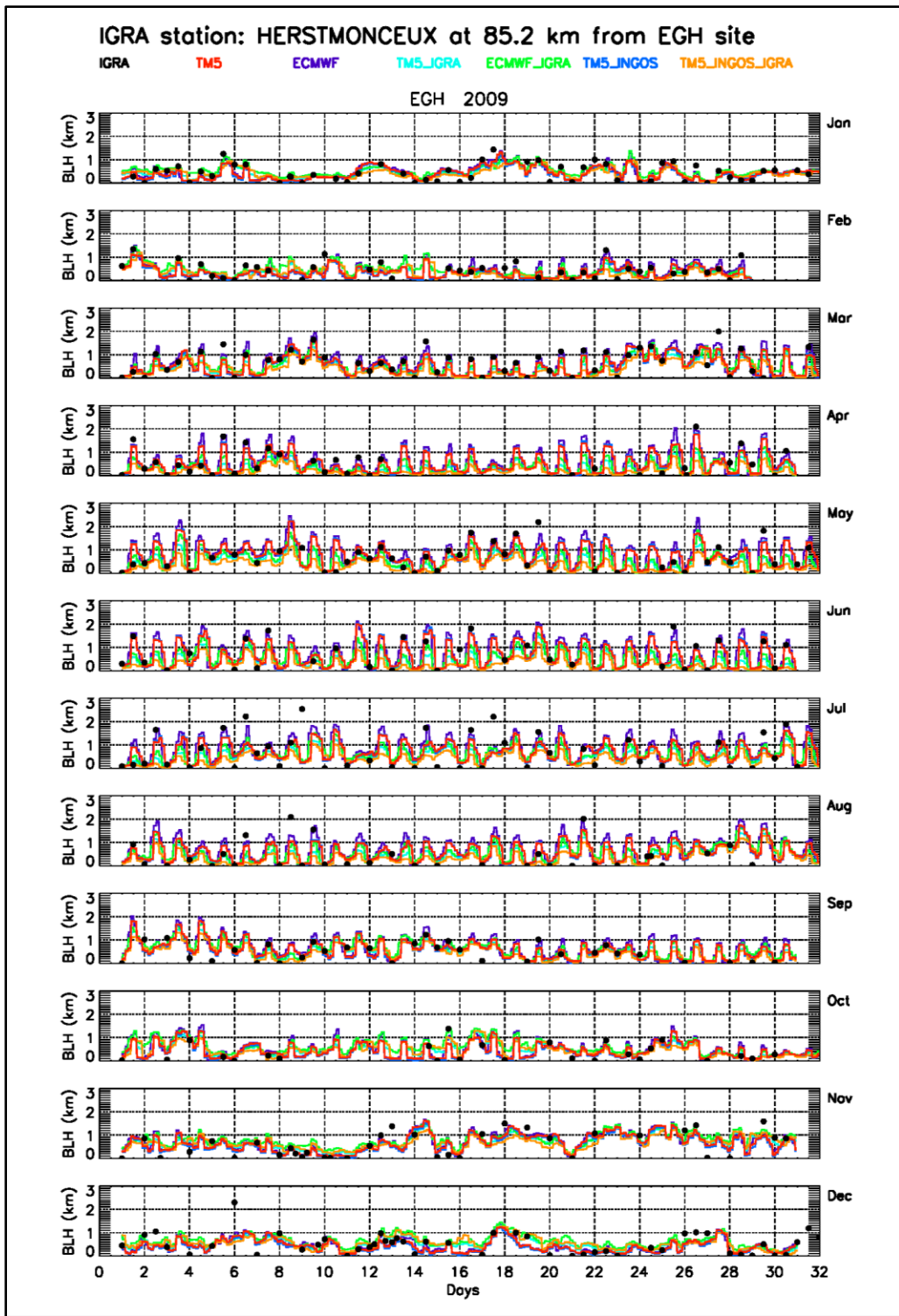


Figure S7: As Figure S2, but for InGOS station Egham (EGH)

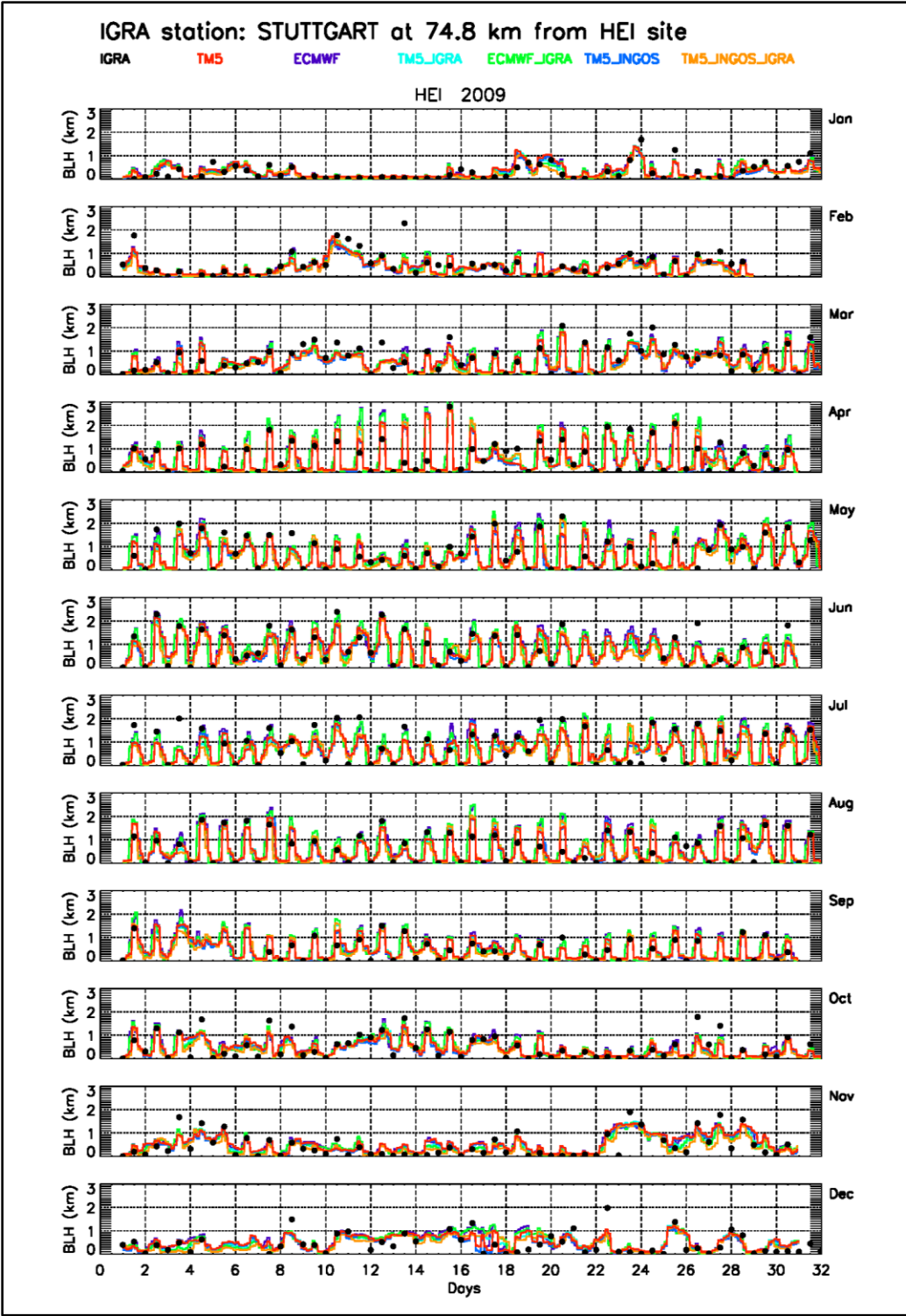


Figure S8: As Figure S2, but for InGOS station Heidelberg (HEI)

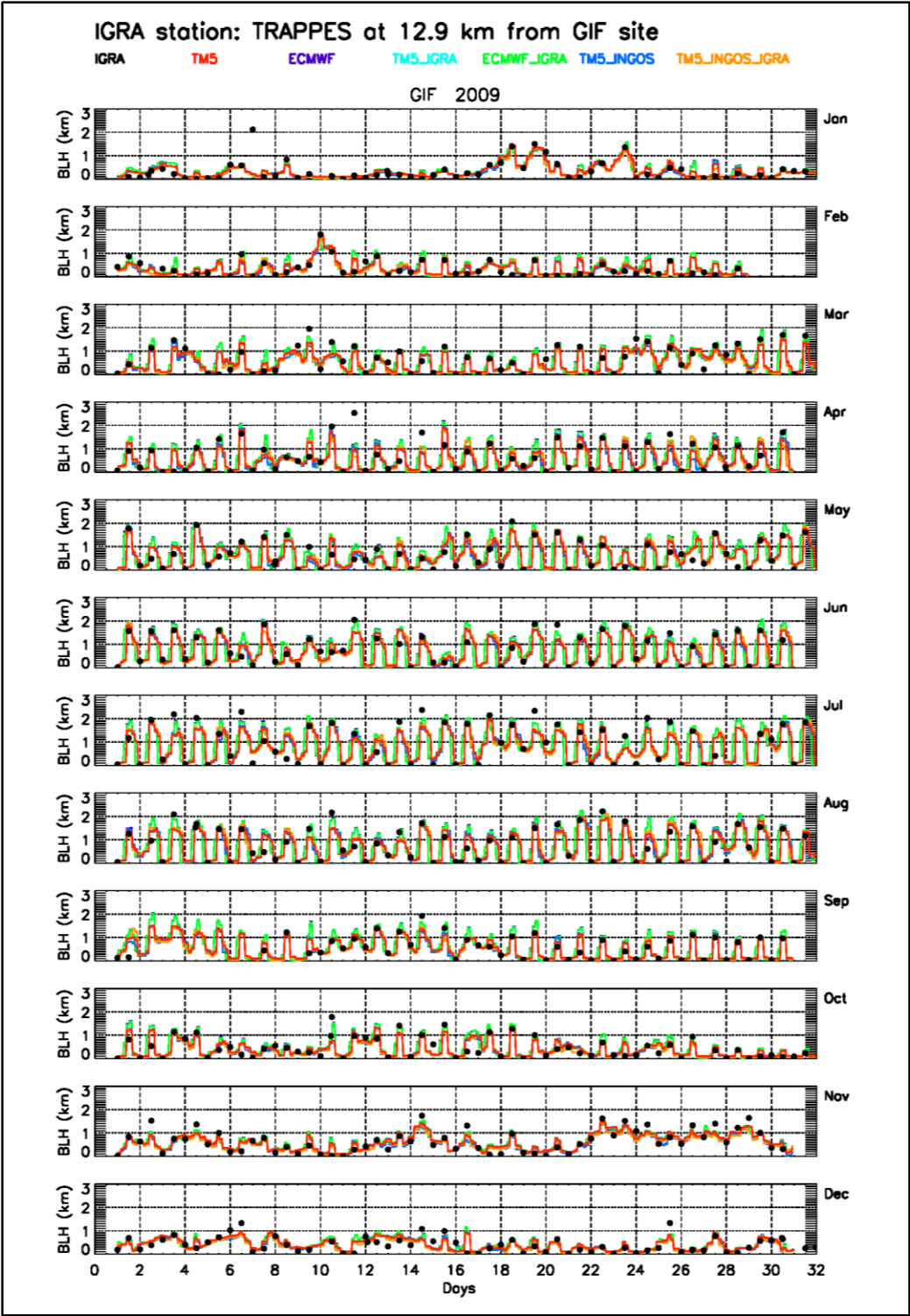


Figure S9: As Figure S2, but for InGOS station Gif sur Yvette (GIF)

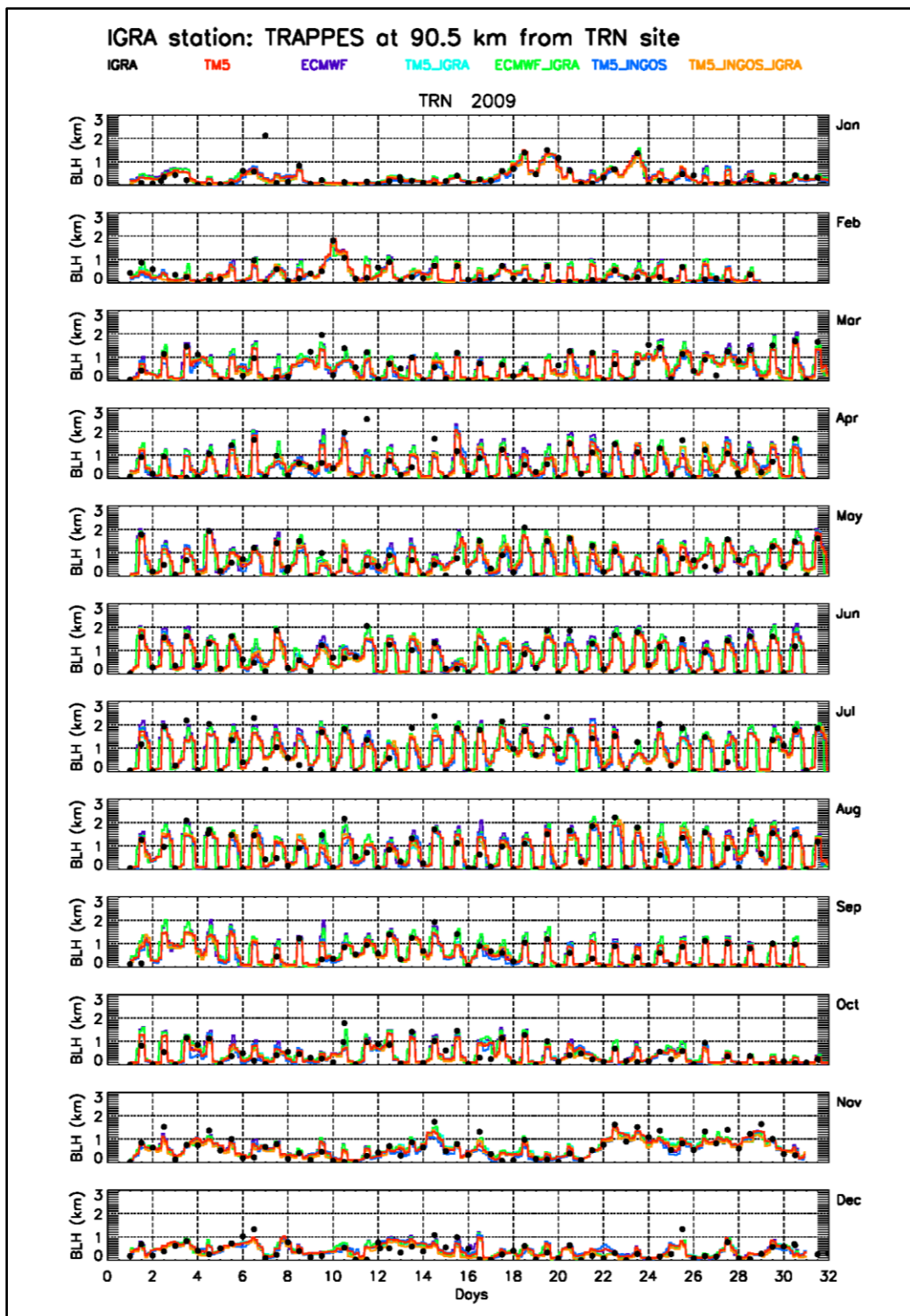


Figure S10: As Figure S2, but for the InGOS station Trainou (TRN or TR4)

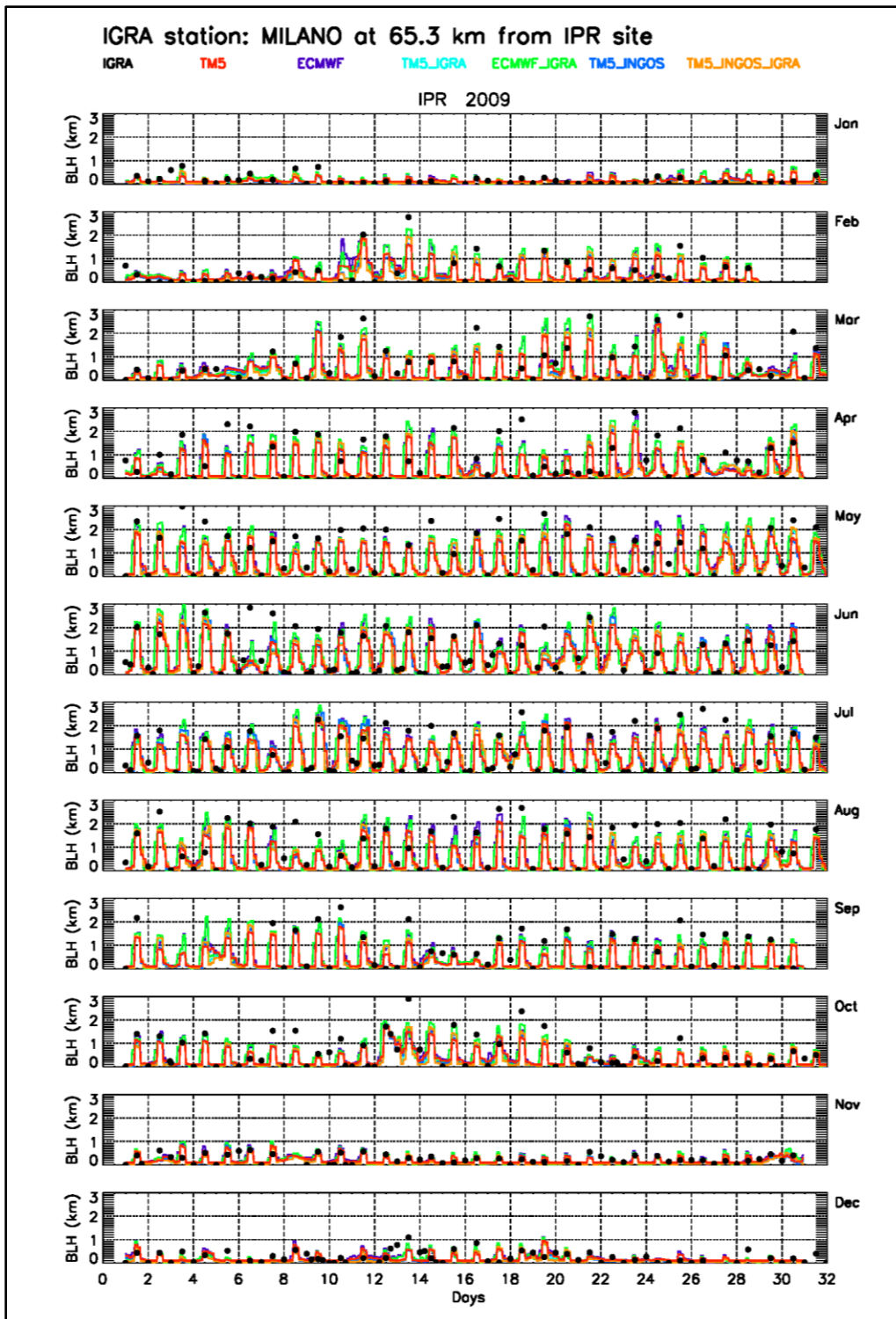


Figure S11: As Figure S2, but for the InGOS station Ispra (IPR)

Mean Seasonal Variations of the Boundary layer heights at the studied stations

We mainly show the ratios between modelled simulations and observations

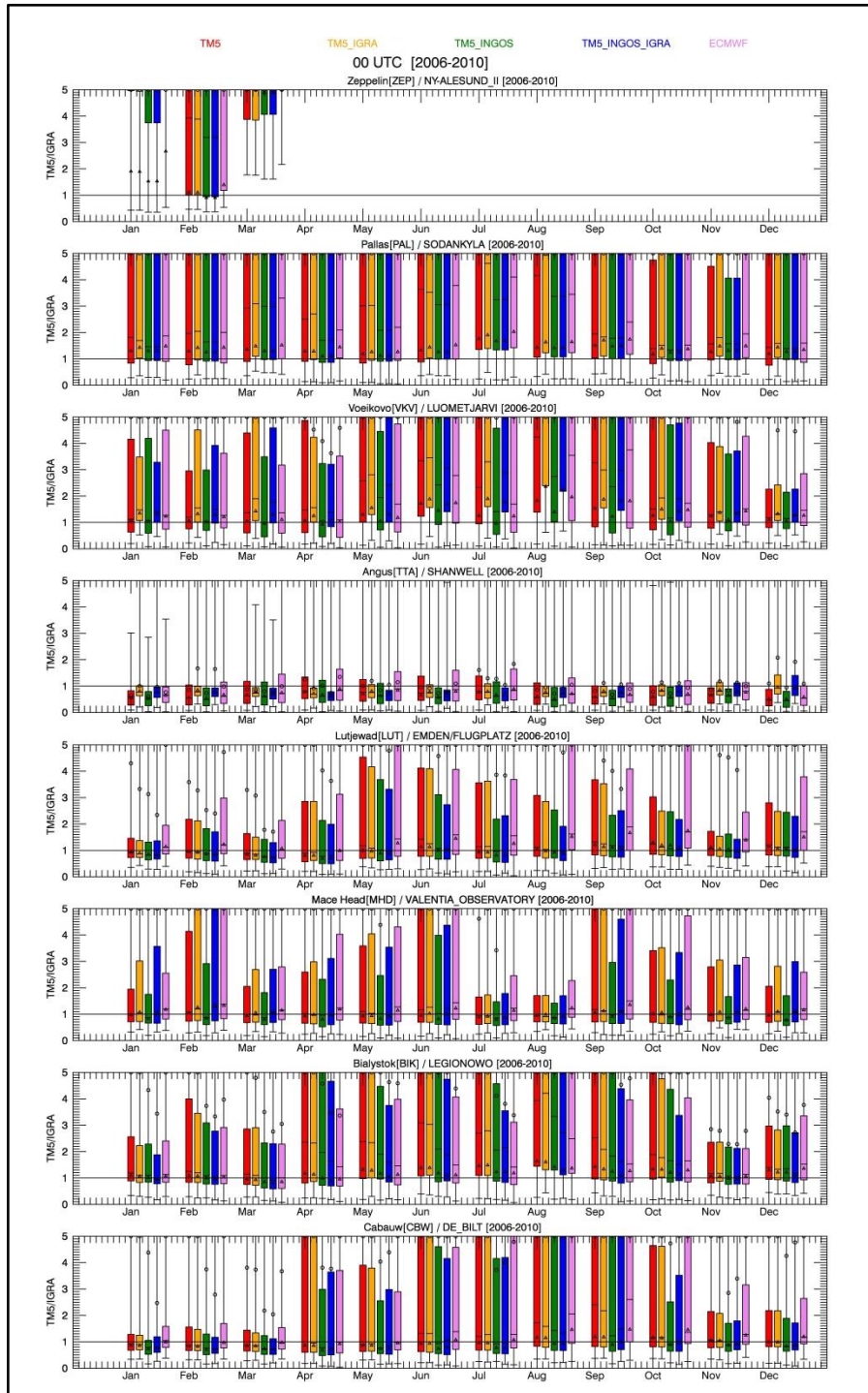


Figure S12: Ratios between modelled (TM5, TM5_IGRA, TM5_INGOS, and TM5_INGOS_IGRA, ECMWF in colors) and IGRA boundary layer heights relevant for INGOS stations and over 2006-2010 at 00 UTC are shown. The name of InGOS station for each graph is shown in the title in left hand side and the relevant IGRA on the right side and the two names are separated by the first slash. The minimum and maximum values of each data set are shown. The boxes are delimited by the 25% and 75% percentiles. The median values are given by the horizontal line in the boxes. The mean values are given by the open circles. The different acronyms are defined in Section 4 of the text. Triangles stand for the ratios between the mean of model data and the mean of IGRA data

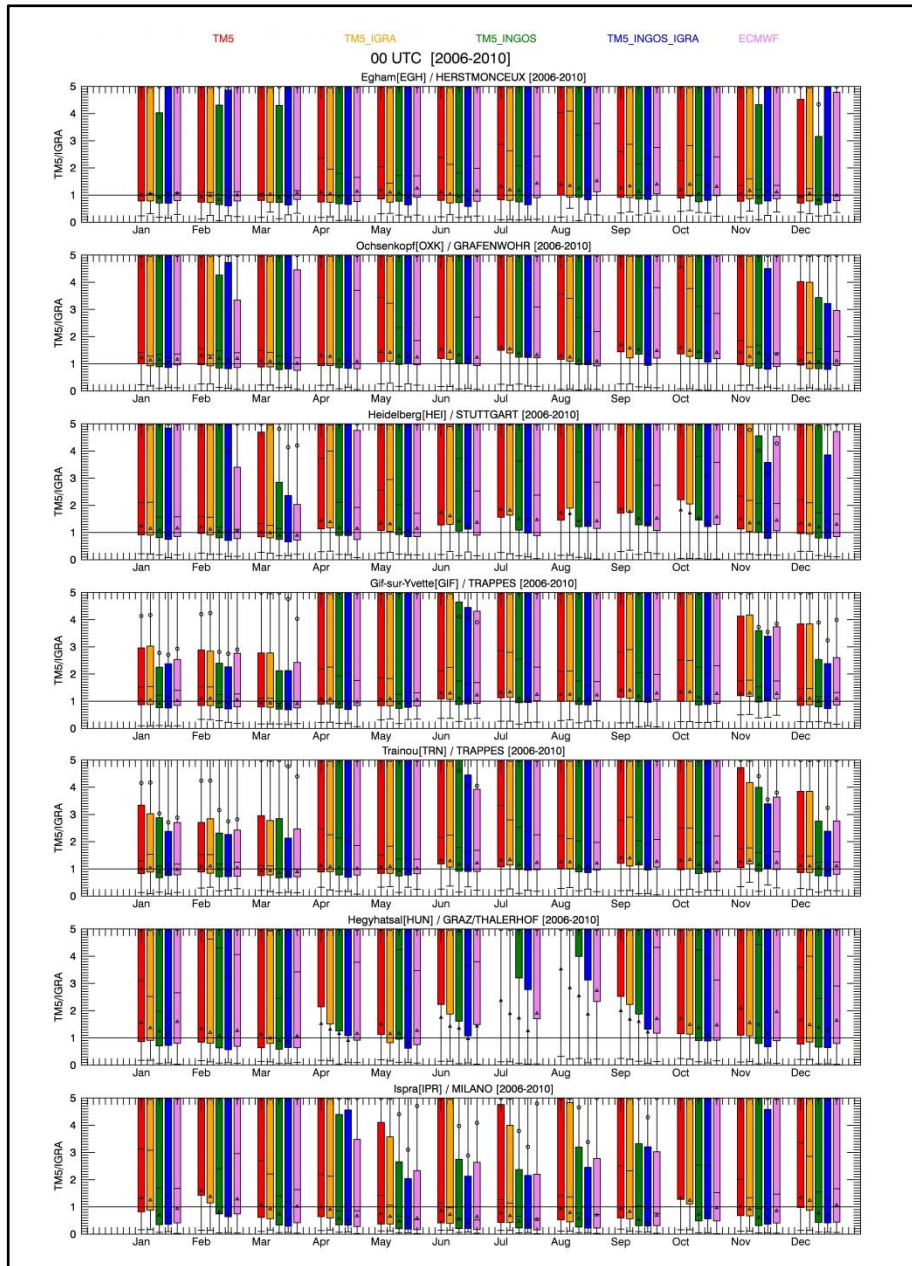


Figure S12: continued

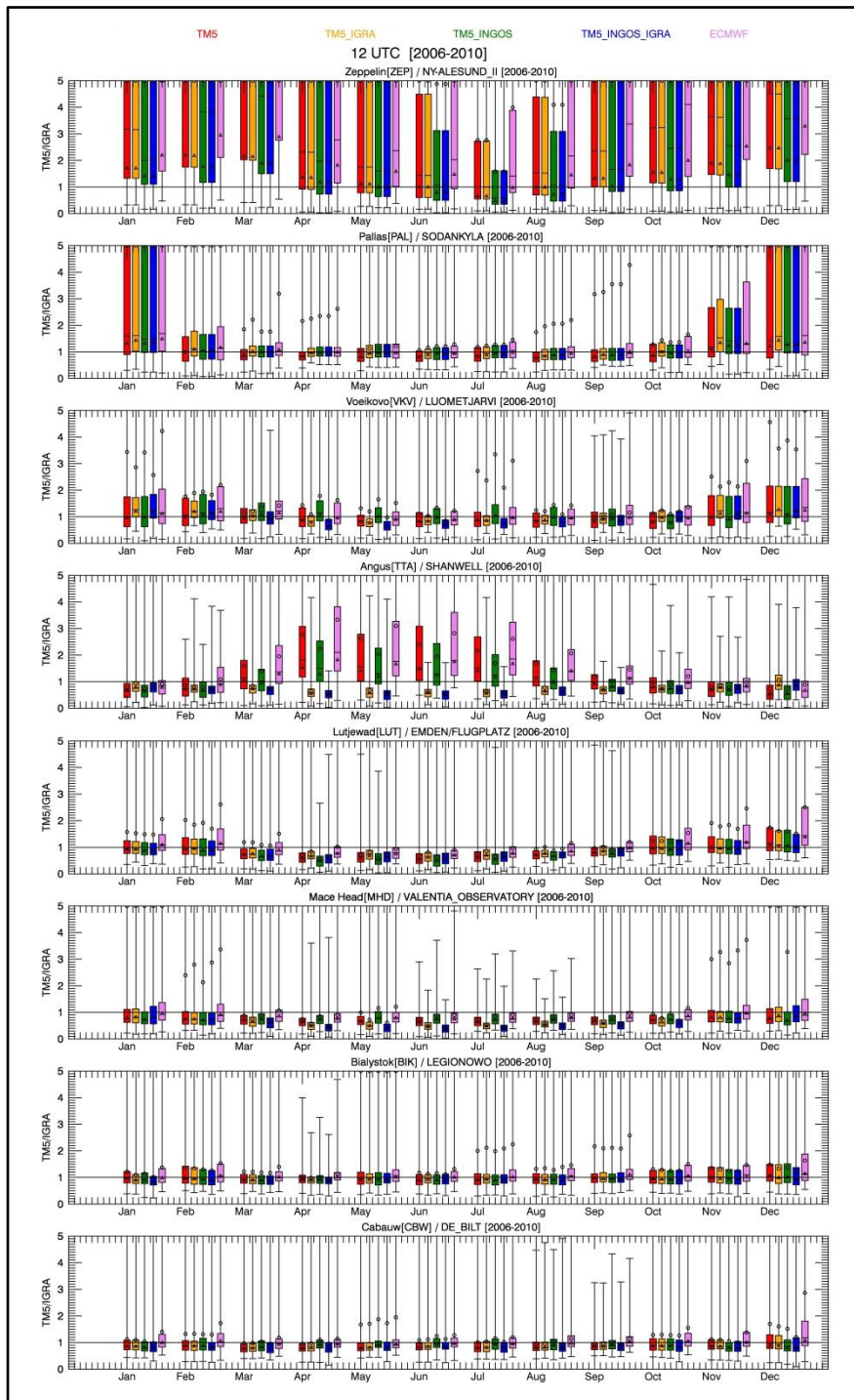


Figure S13: As Figure S12, but at 12 UTC

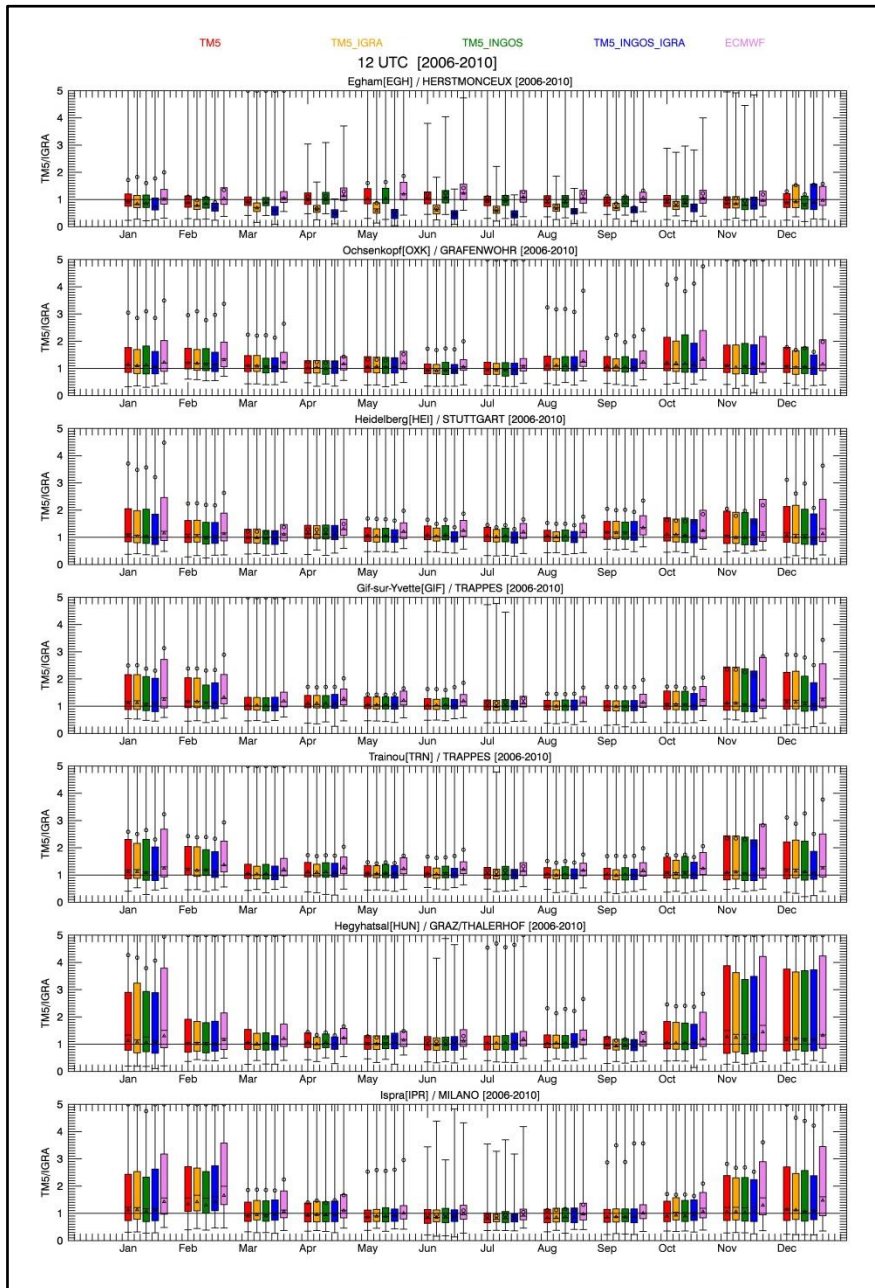


Figure S13: continued

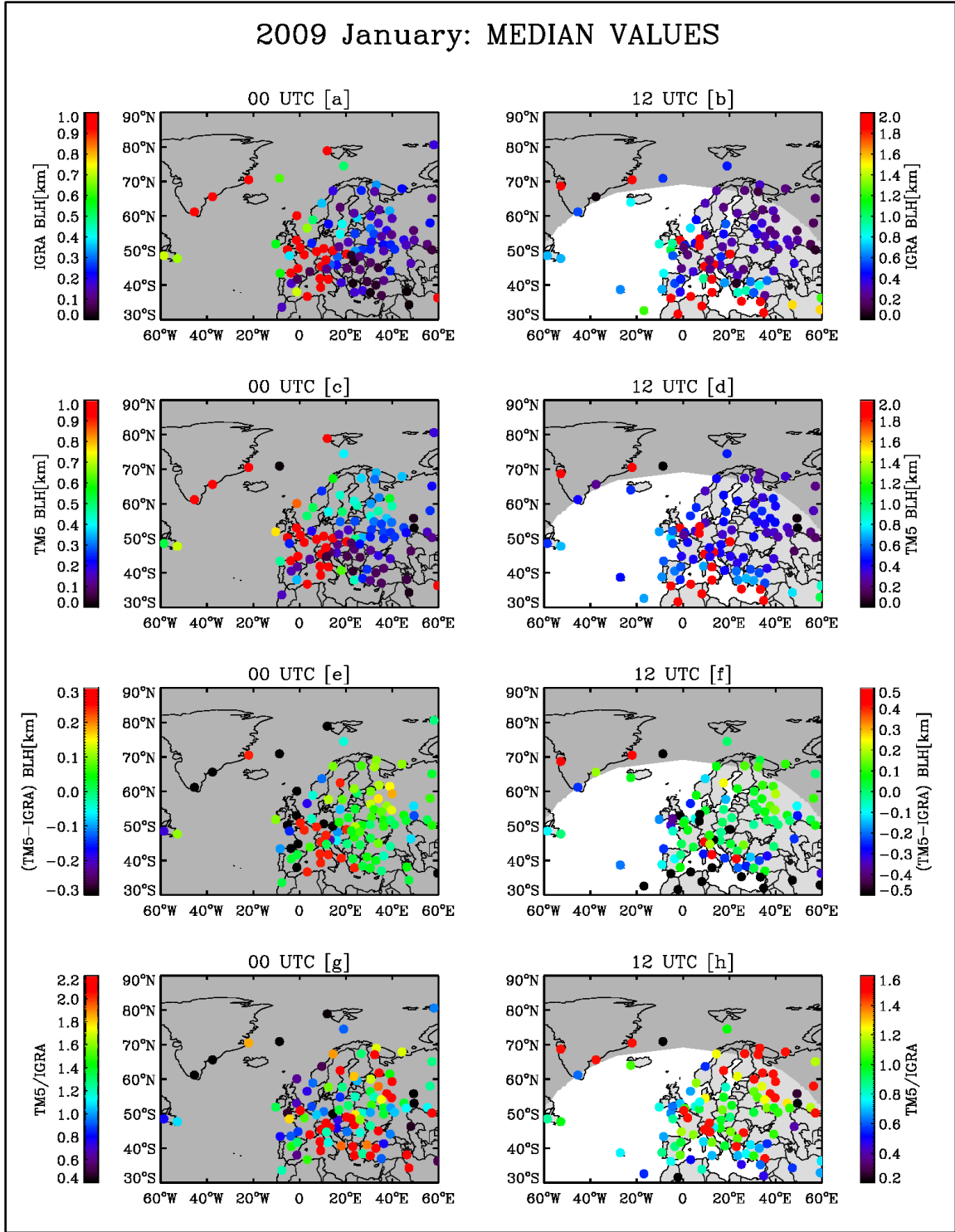


Figure S14: Median values of IGRA and TM5 boundary layer heights [a, b, c, and d] together with their differences (TM5-IGRA) [e and f] for January 2009 are shown. The median values of the ratios between TM5 and IGRA boundary layer heights (TM5/IGRA) [g and h] are also displayed. Left: 00UTC; right: 12 UTC.

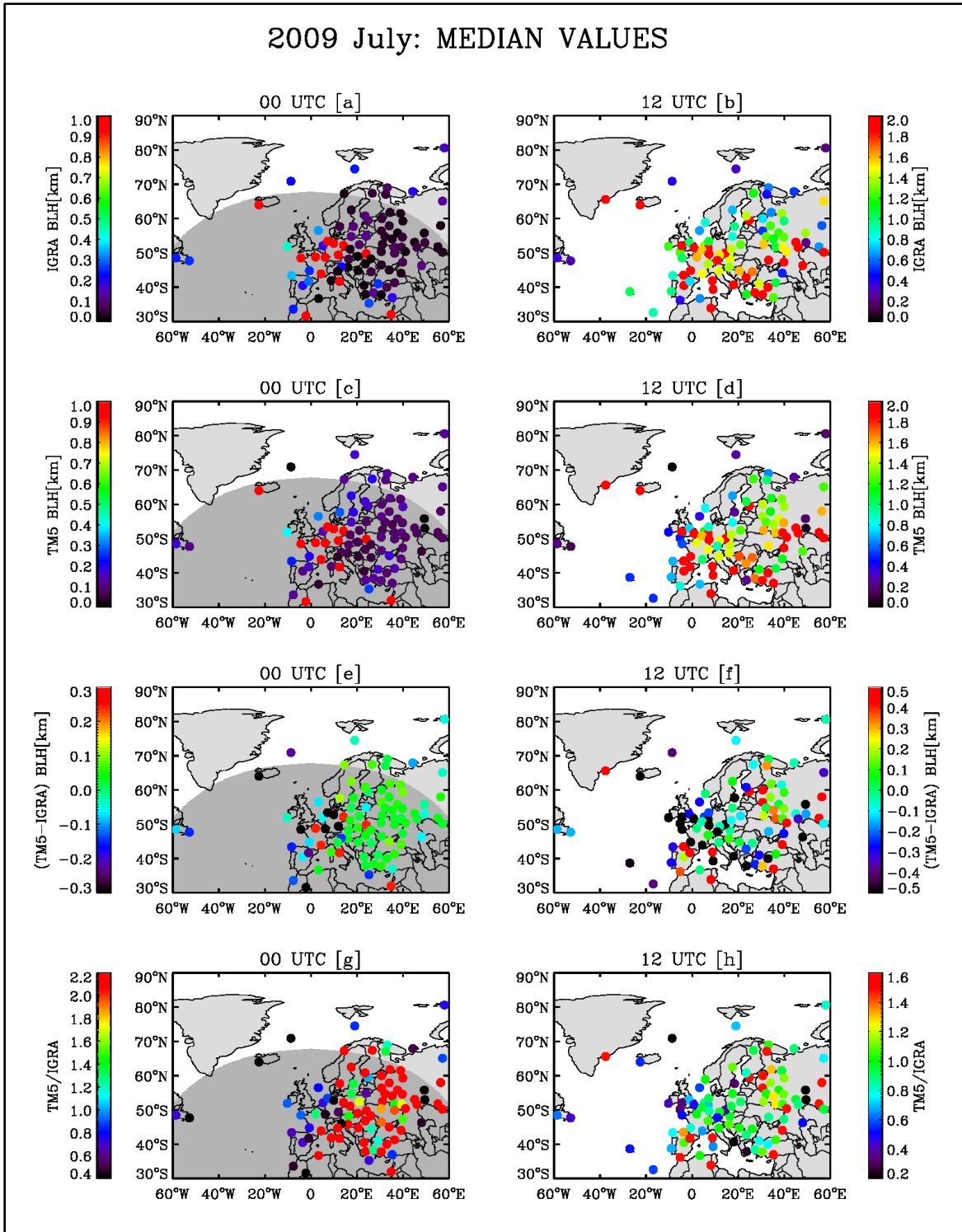


Figure S15: As for Figure S14, but for July 2009

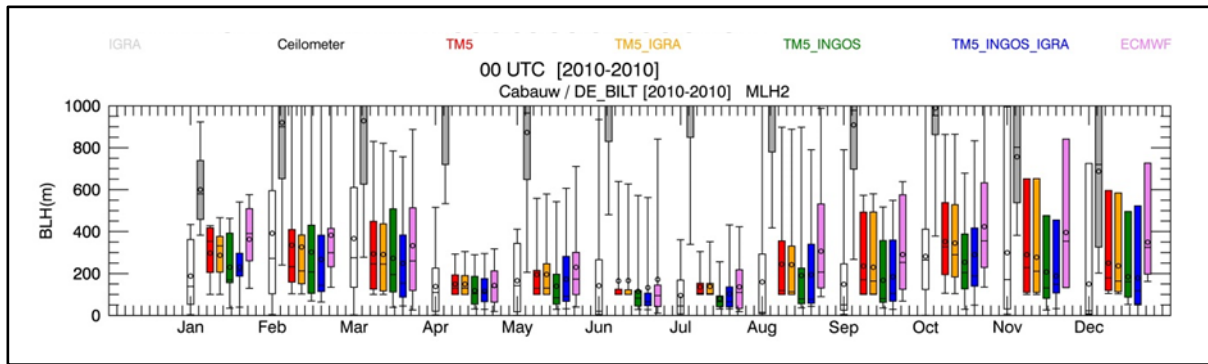


Figure S16: Observed (IGRA and ceilometer) and modelled (TM5, TM5_IGRA, TM5_INGOS, and TM5_INGOS_IGRA, ECMWF) boundary layer heights at Cabauw at 00 UTC and for the year 2010 are shown. The name of InGOS station is shown in the title in left hand side and the relevant IGRA on the right side and the two names are separated by the first slash. The minimum and maximum values of each data set are shown. The boxes are delimited by the 25% and 75% percentiles. The median values are given by the horizontal line in the boxes. The mean values are given by the open circles. The IGRA data are in blank, the ceilometer data are in black and the various colors stand for the various boundary layer heights from TM5 and ECMWF models. The different acronyms are defined in Section 4 of the text.

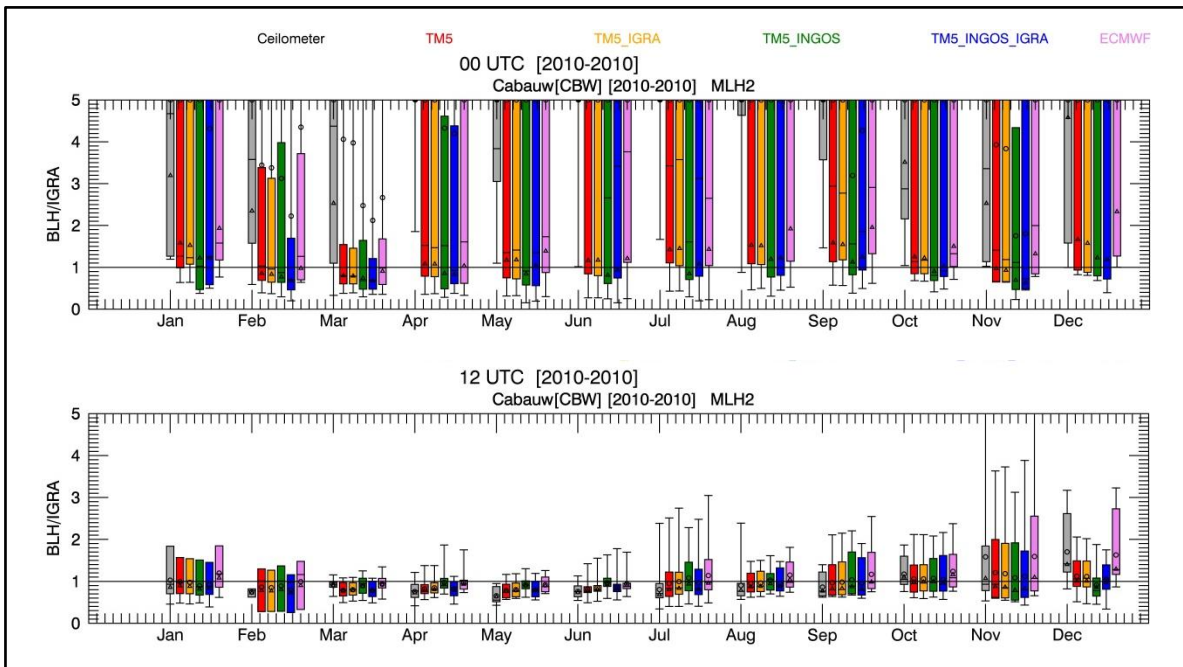


Figure S16b: As Figure S12, but at Cabauw where both ceilometer and IGRA data are available. Ratios of both ceilometer (black) and simulated (in colors) versus IGRA boundary layer heights (De Bilt) at 00 and 12 UTC and for the year 2010 are shown. The different acronyms are defined in Section 3 of the text

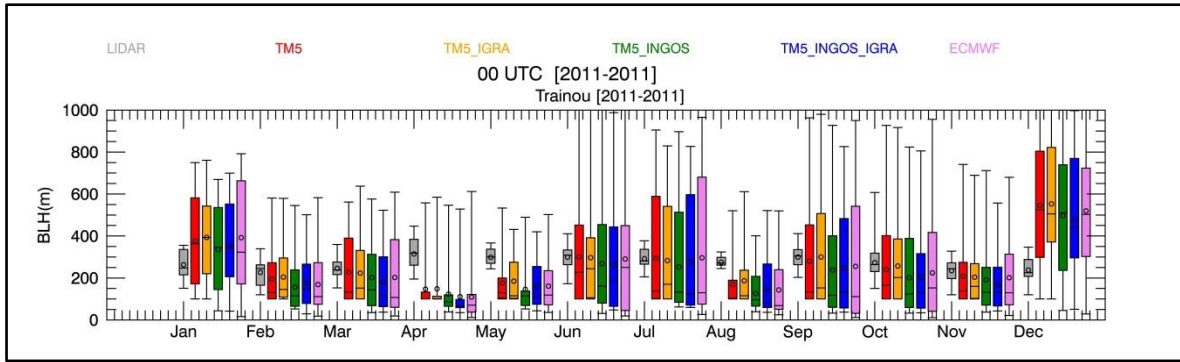


Figure S17: Observed (lidar) and modelled (TM5, TM5_IGRA, TM5_INGOS, and TM5_INGOS_IGRA, ECMWF) boundary layer heights at Trainou at 00 UTC and for the year 2011 are shown. The name of InGOS station is shown in the title in left hand side and the relevant IGRA on the right side and the two names are separated by the first slash. The minimum and maximum values of each data set are shown. The boxes are delimited by the 25% and 75% percentiles. The median values are given by the horizontal line in the boxes. The mean values are given by the open circles. The lidar data are in black and the various colors stand for the various boundary layer heights from TM5 and ECMWF models. The different acronyms are defined in Section 4 of the text.

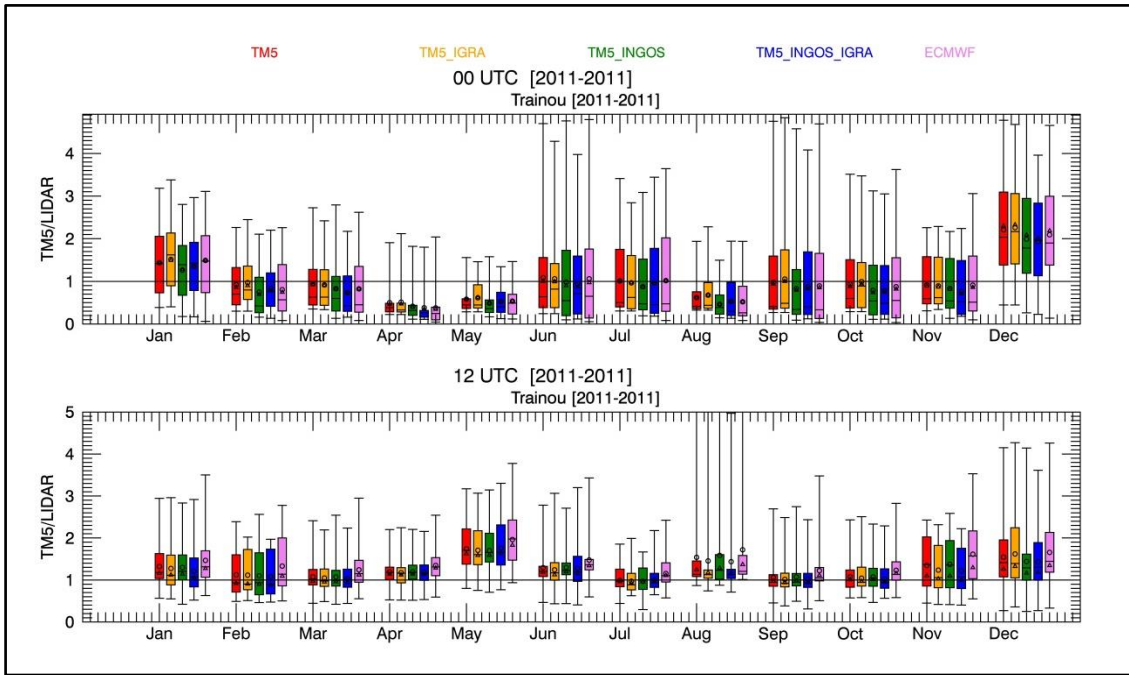


Figure S17b: As Figure S12, but at Trainou where lidar data are available. Ratios between simulated (in colors) and lidar (black) boundary layer heights at 00 and 12 UTC for the year 2011 are shown. The different acronyms are defined in Section 3 of the text

Time series of ^{222}Rn activity concentrations

We simulate ^{222}Rn concentrations using either the InGOS ^{222}Rn flux map, or constant ^{222}Rn fluxes (see Section 3.3). Furthermore, we apply four different convection schemes in the TM5 model (for the InGOS ^{222}Rn flux map based simulations only). These different simulations are labelled by the following acronyms:

- FC_CT: constant ^{222}Rn fluxes, and default convection scheme in TM5 based on *Tiedtke* [1989]
- FI_CT: InGOS ^{222}Rn flux map, and default convection
- FI_CS: InGOS ^{222}Rn flux map and updated treatment of slopes in the TM5 convection scheme (see Section 3.1 of the text)
- FI_CE: InGOS ^{222}Rn flux map and the updated convection scheme based on ECMWF reanalyses (see Section 3.1 of the text)
- FI_CU: InGOS ^{222}Rn flux map, updated treatment of slopes and updated convection scheme based on ECMWF

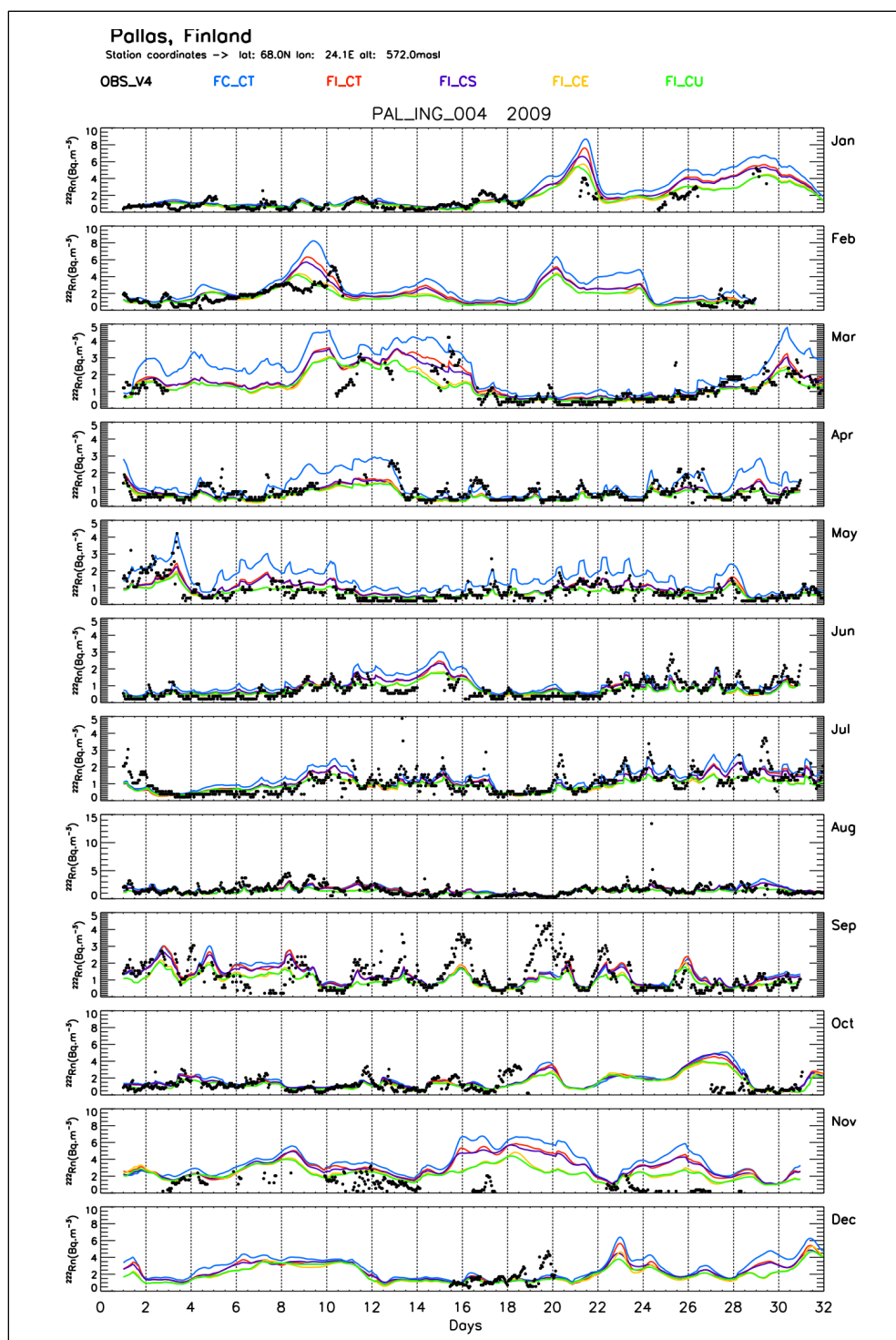


Figure S18: The time series of the observed and simulated radon activity concentrations at Palas [PAL] for 2009. The observed radon concentrations are in big dots (●). The model simulations are obtained from constant emissions (solid blue line; FC_CT) and four from INGOS emissions (solid red line: FI_CT, solid violet line: FI_CS, solid orange line: FI_CE, and solid green line: FI_CU). The different acronyms are defined in the previous page or in Section 4 of the text

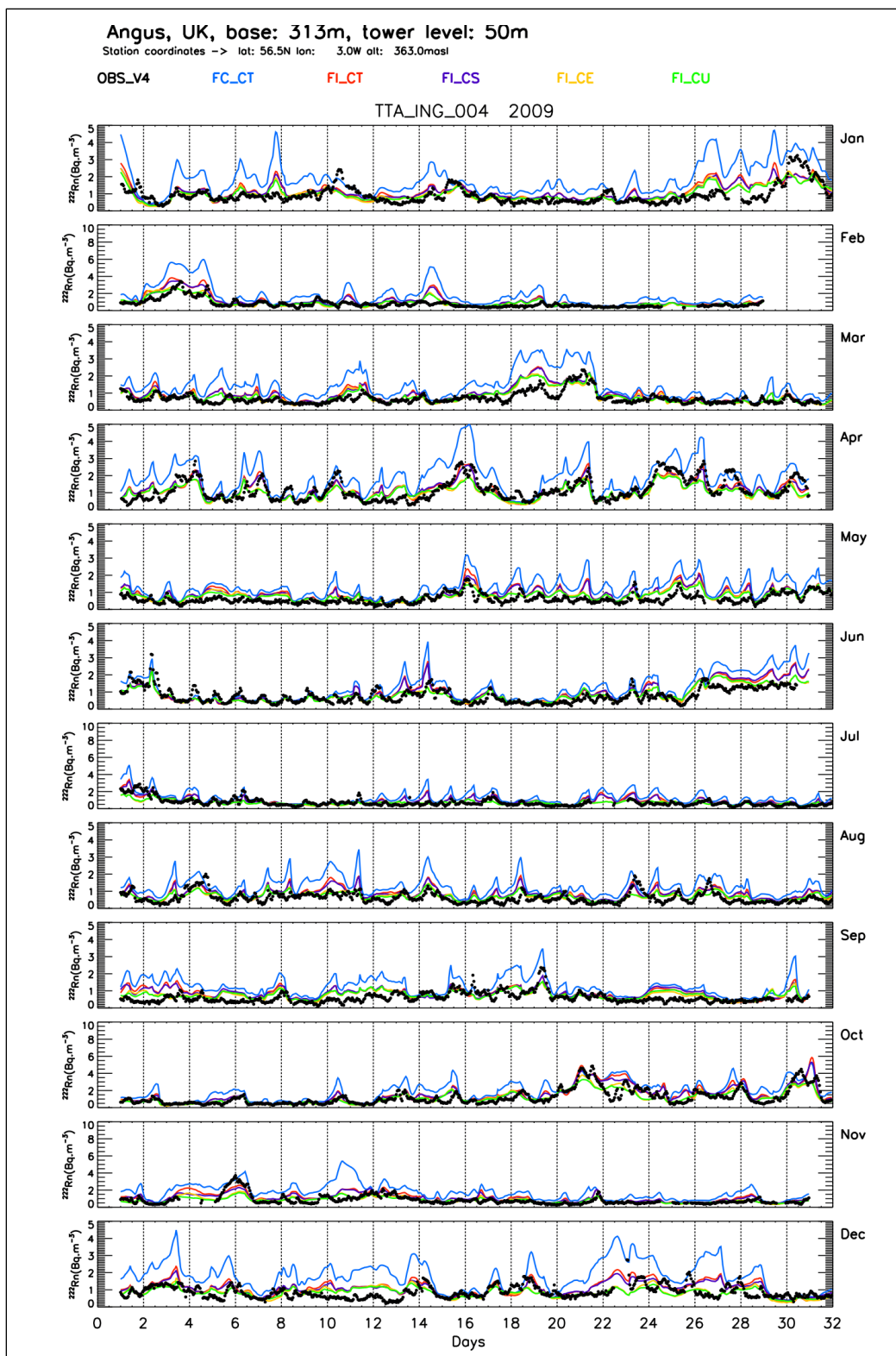


Figure S19: As Figure S18, but at Angus (TTA)

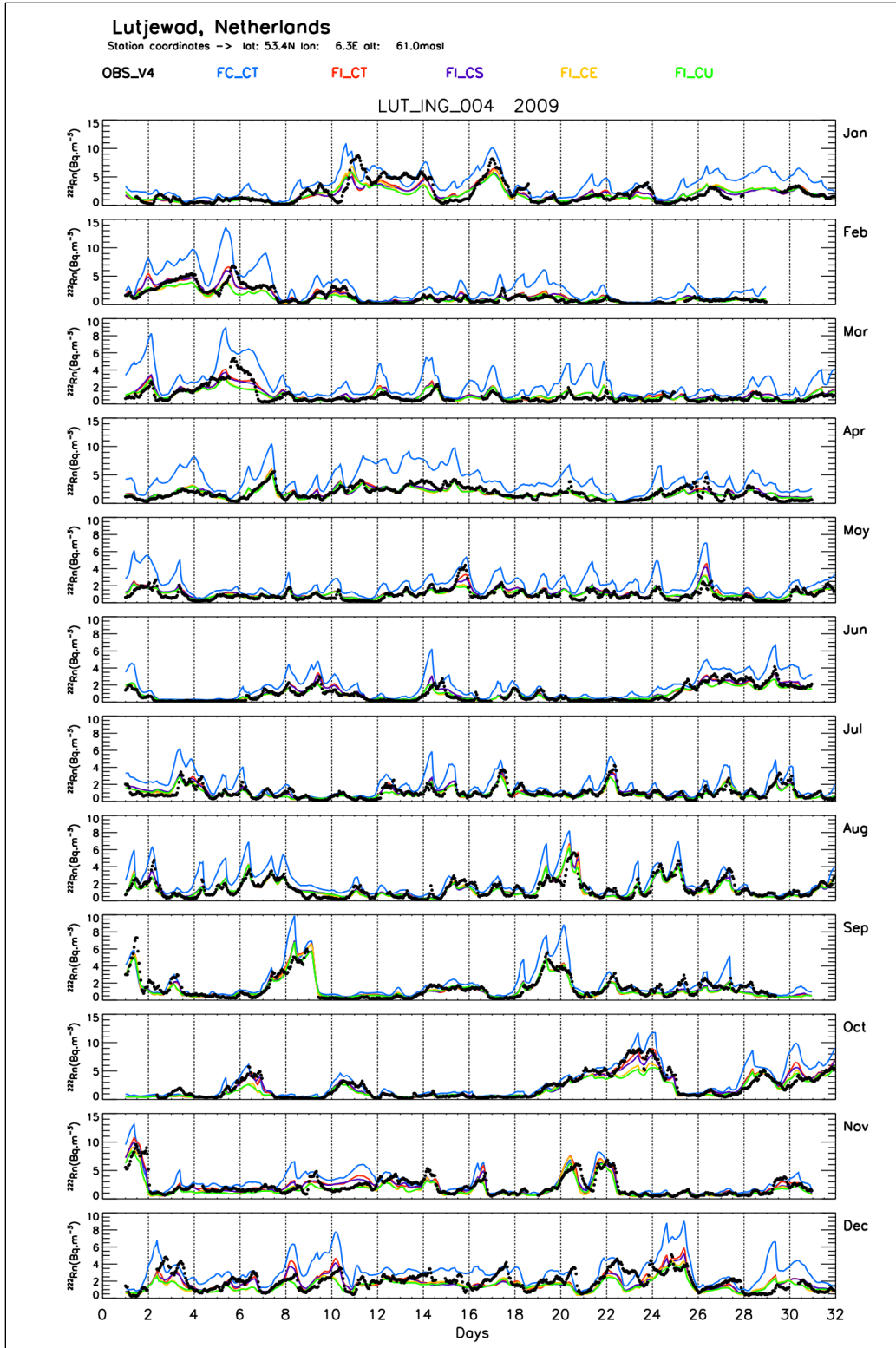


Figure S20: As Figure S18, but at Lutjewad (LUT)

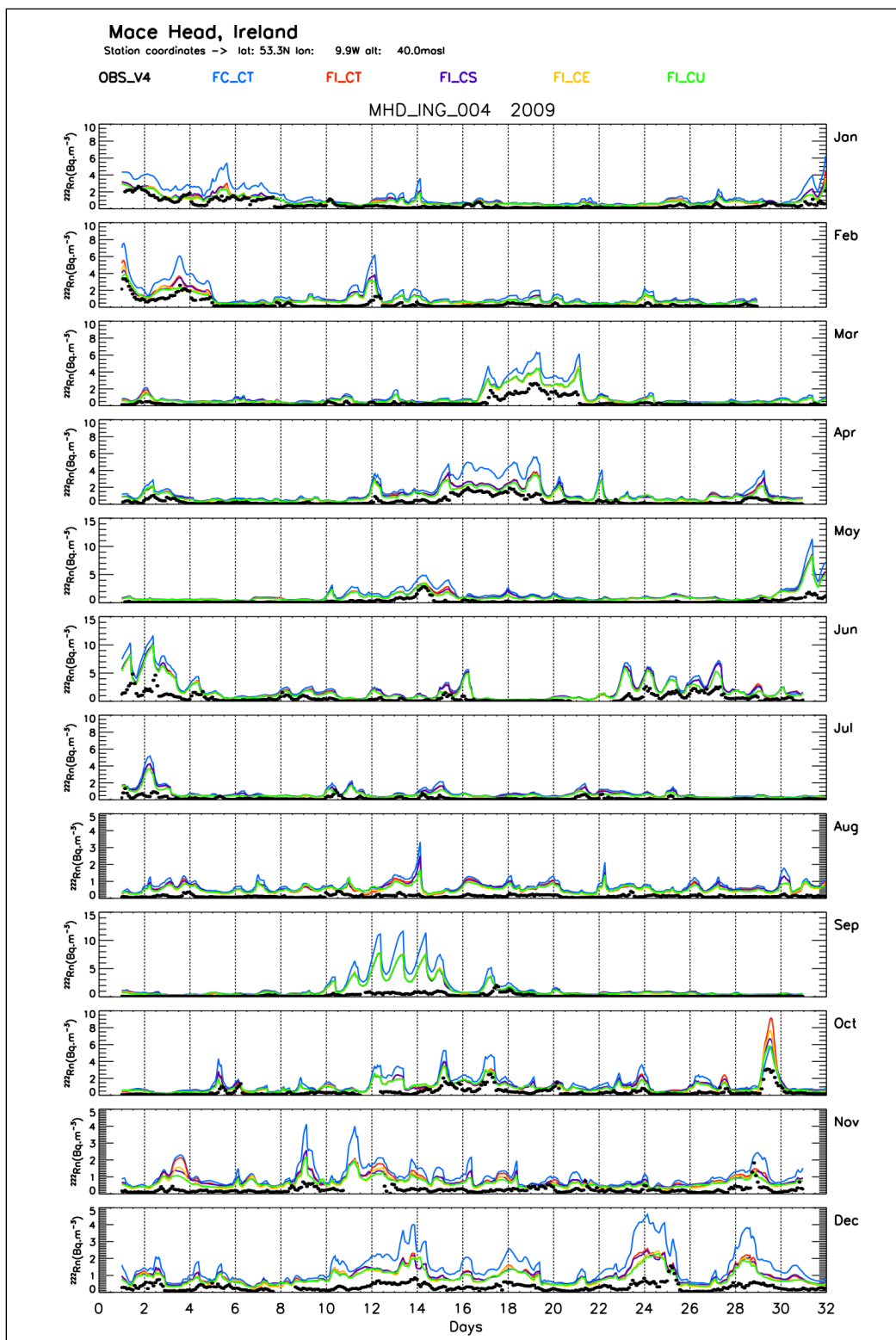


Figure S21: As Figure S18, but at Mace Head (MHD)

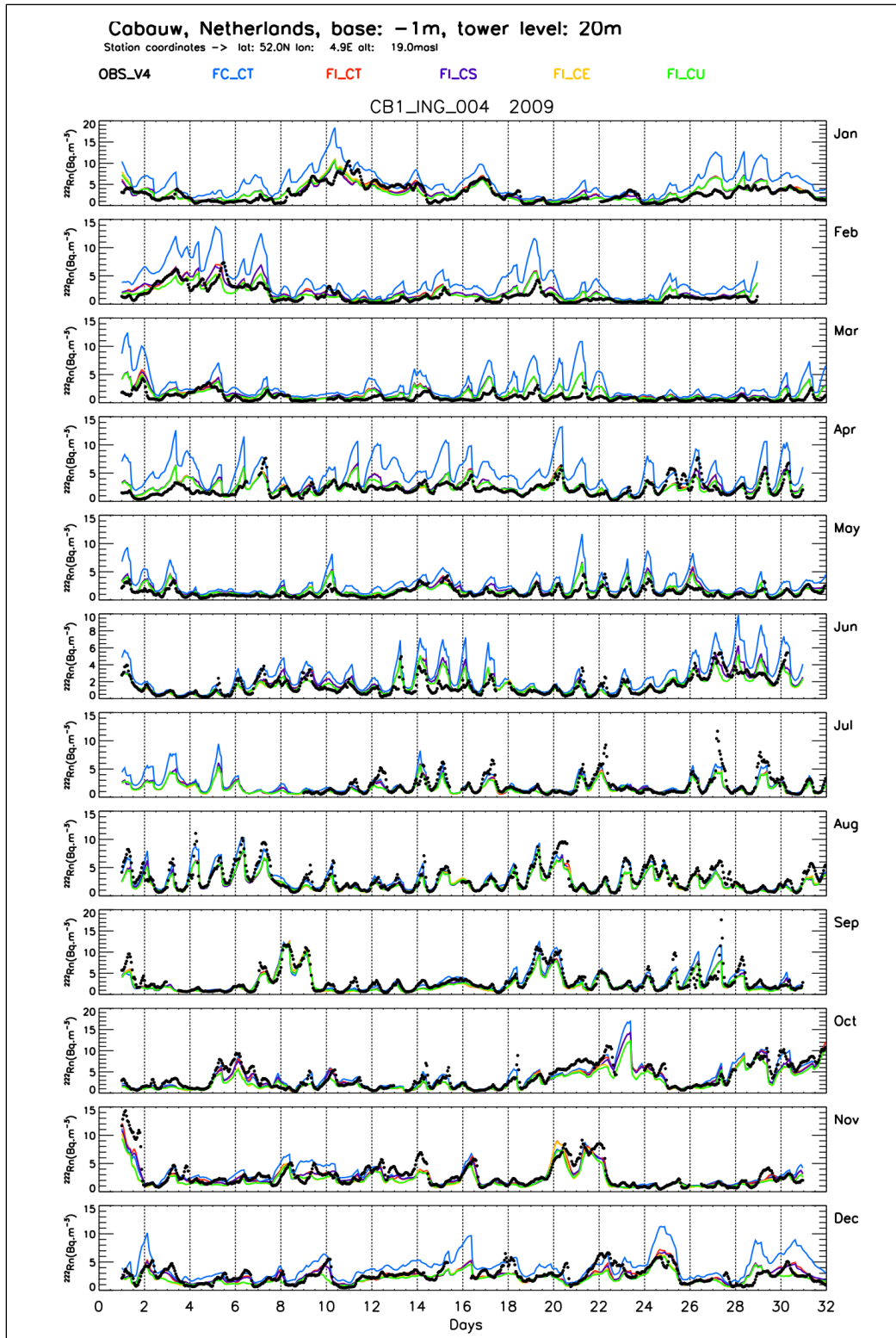


Figure S22: As Figure S18, but for Cabauw at 20 m [CB1]

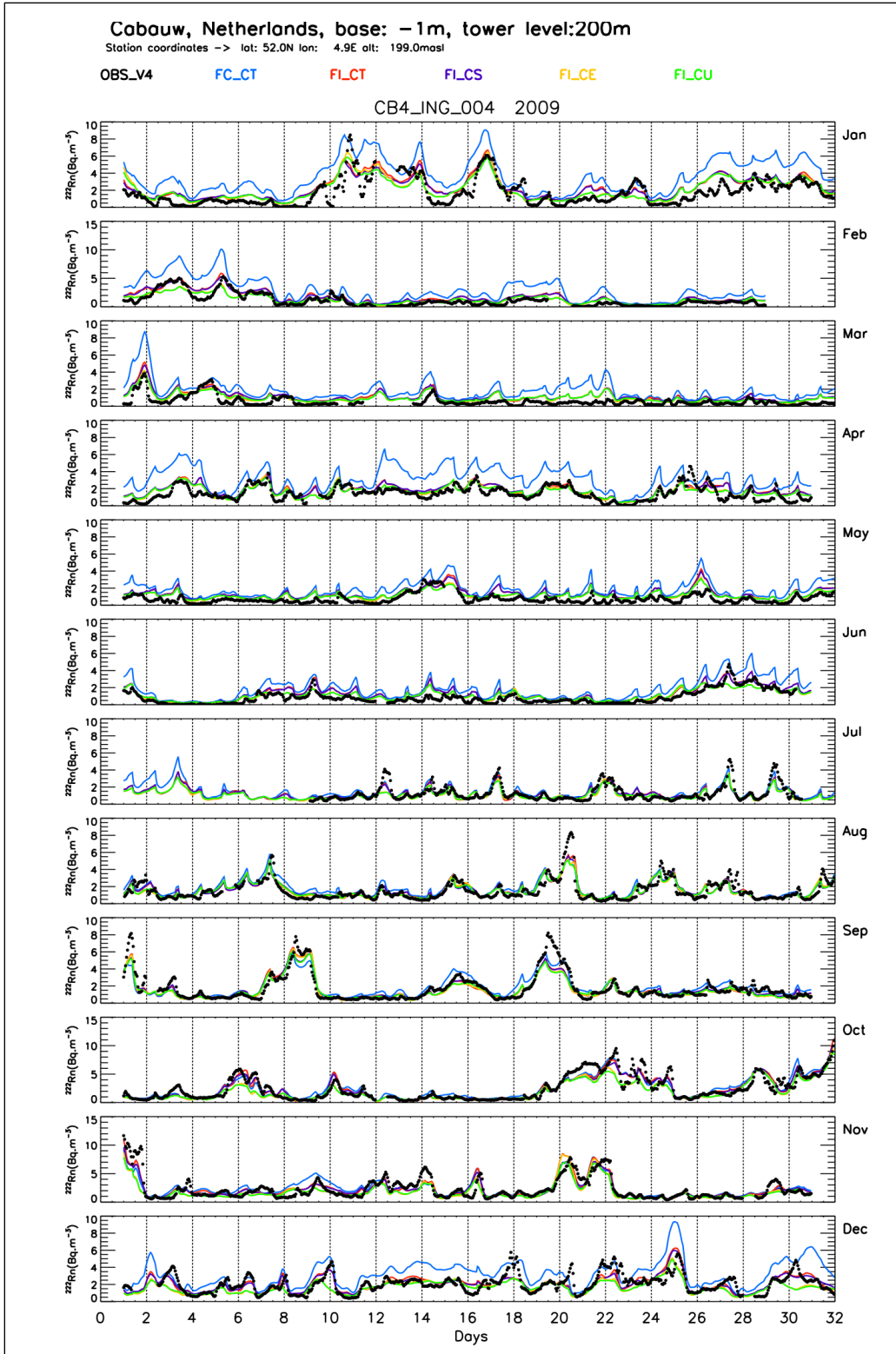


Figure S23: As Figure S18, but for Cabauw at 200 m height [CB4]

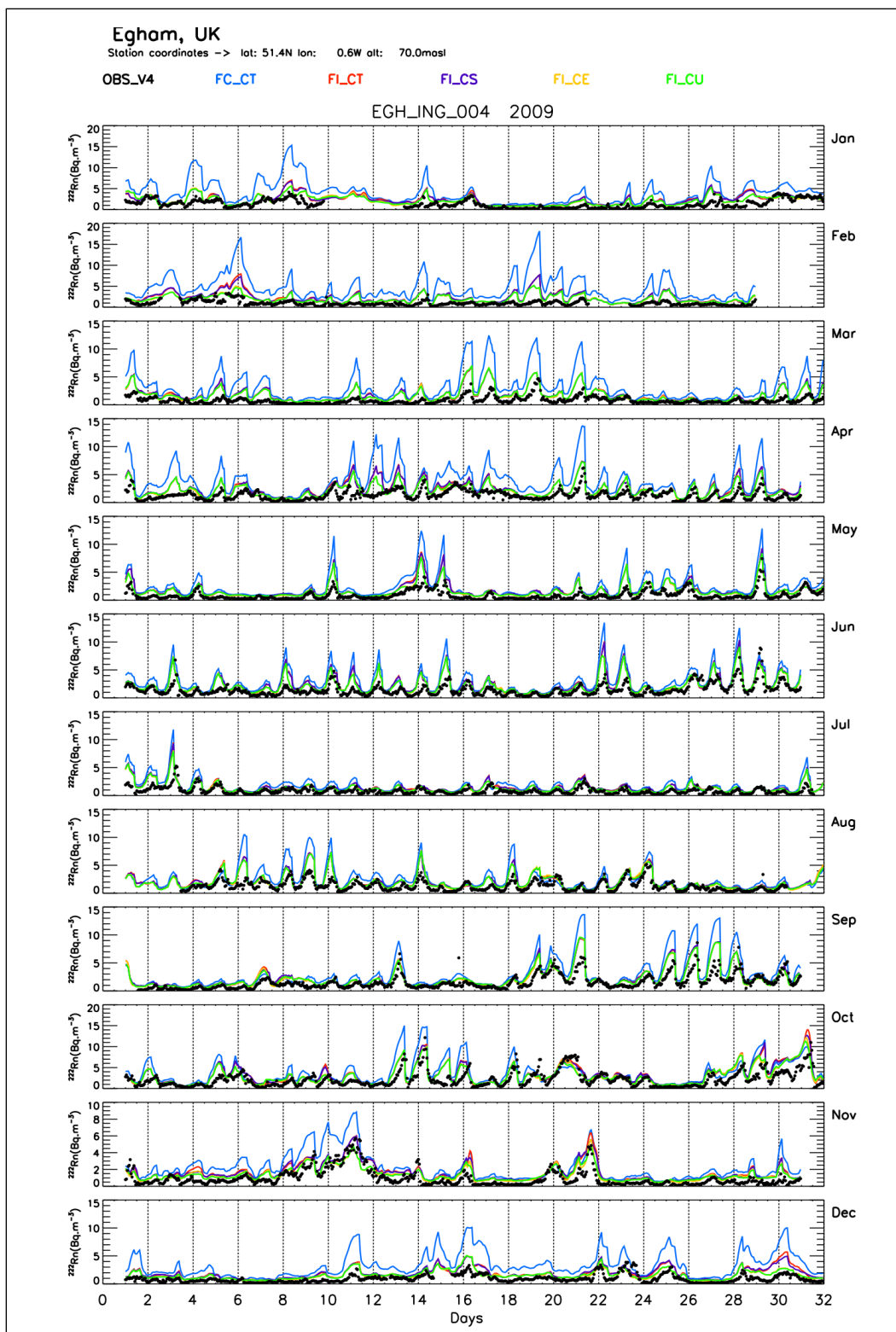


Figure S24: As Figure S18, but at Egham (EGH)

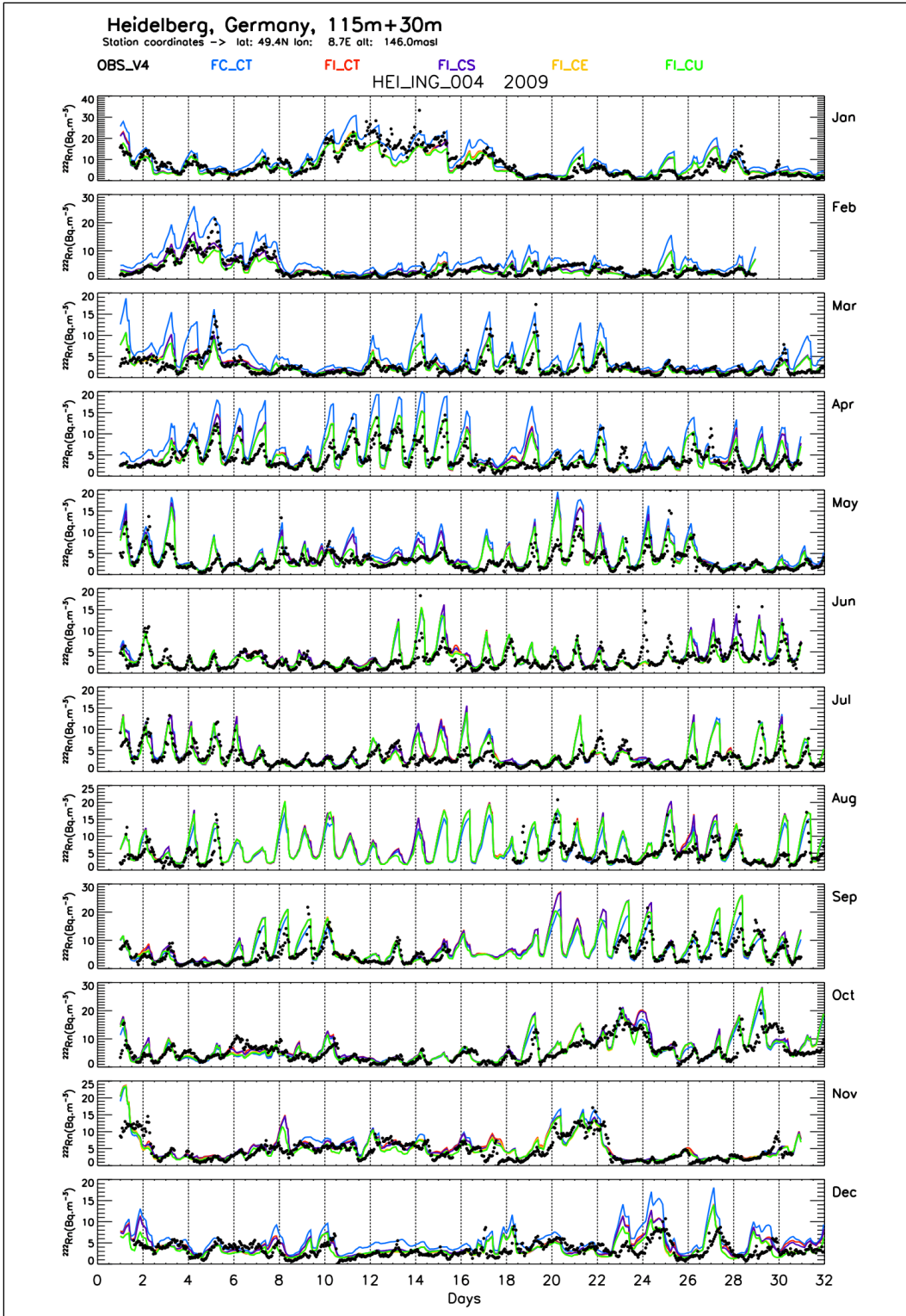


Figure S25: As Figure S18, but at Heidelberg (HEI)

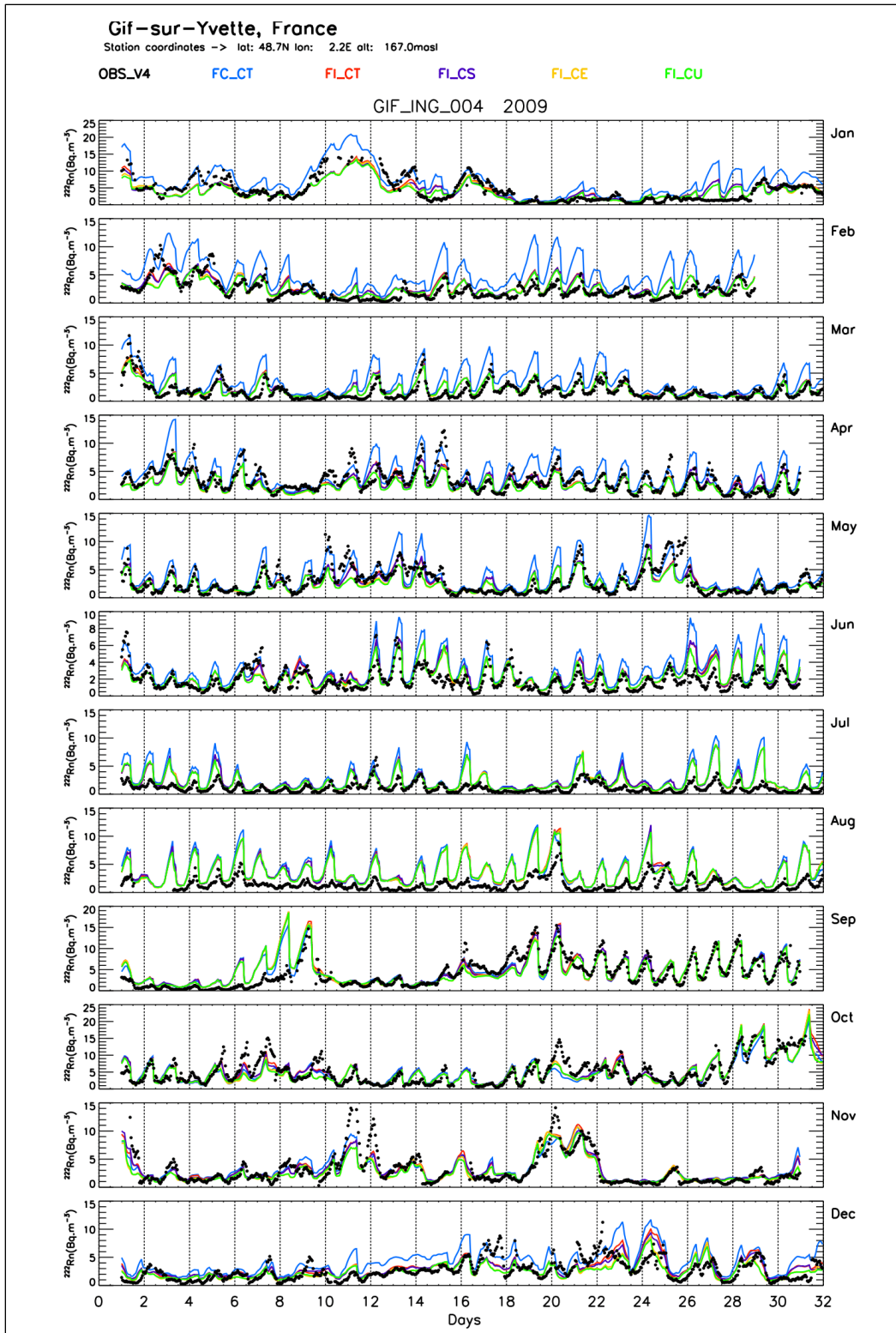


Figure S26: As Figure S18, but at Gif sur Yvette (GIF)

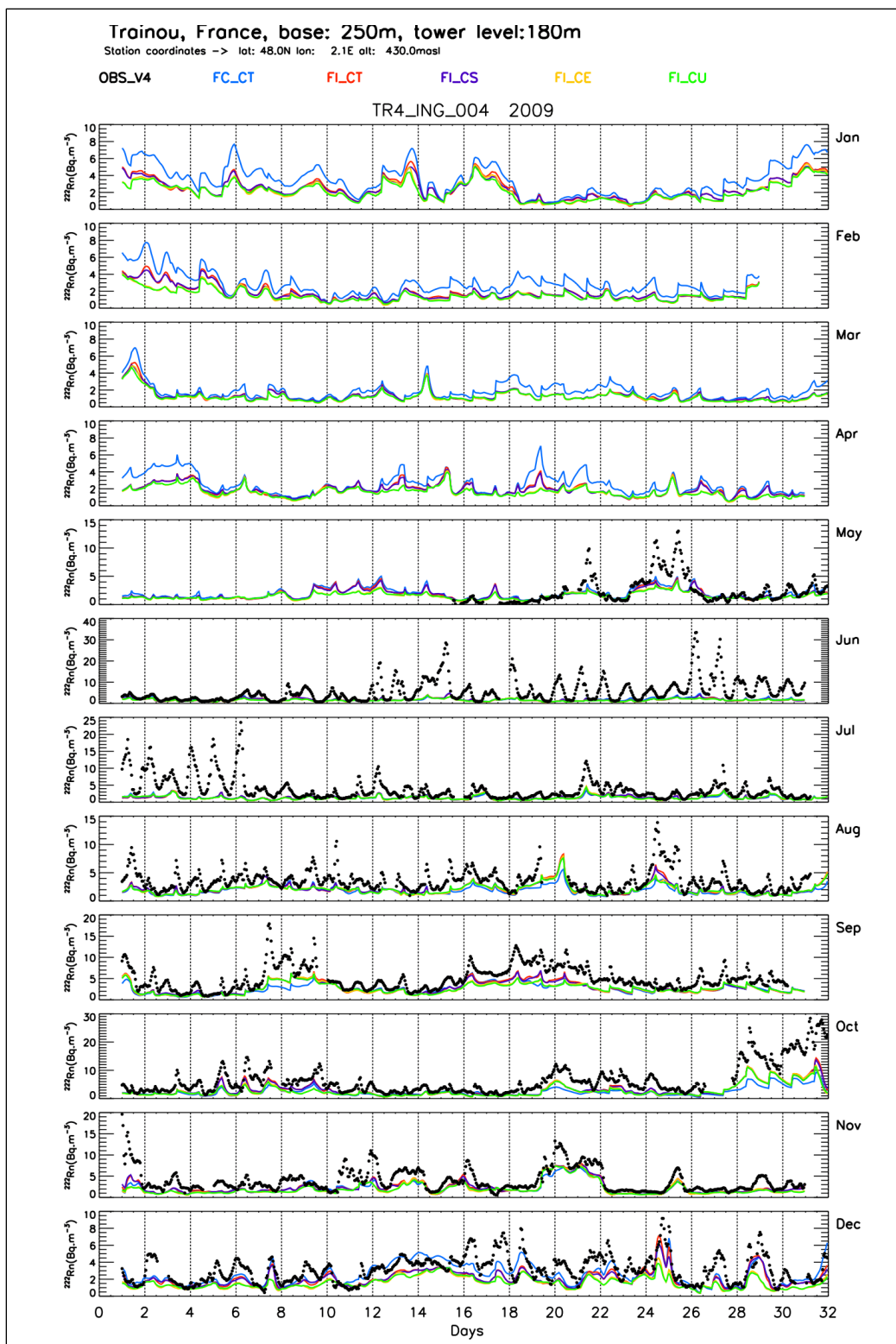


Figure S27: As Figure S18, but for Trainou at 180 m [TR4]

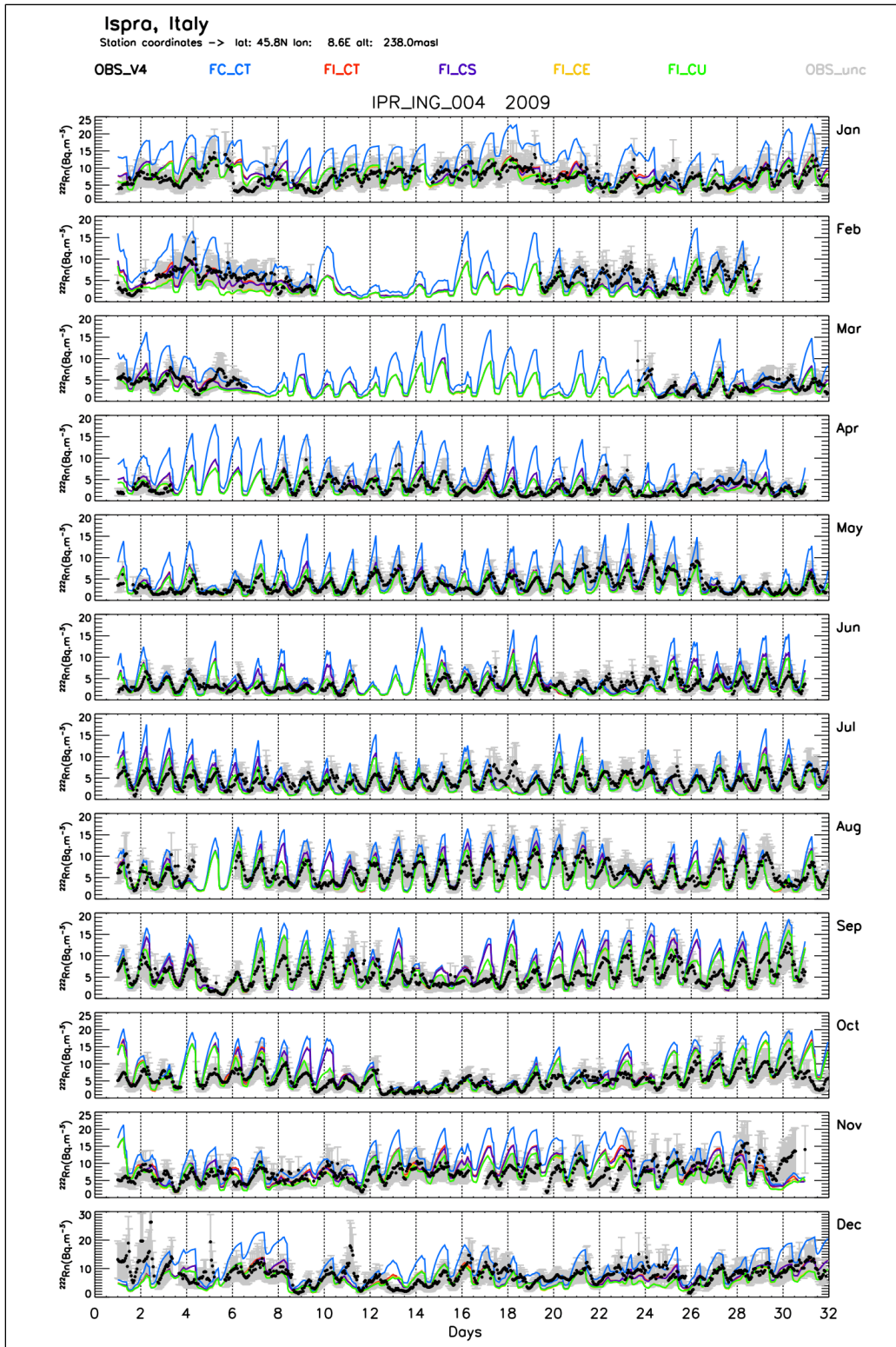


Figure S28: As Figure S18, but at Ispra (IPR). This figure includes also the uncertainties in the ^{222}Rn activity concentrations (grey shaded area) from the wind-speed dependent correction of the measurements ('normalization' to 15m inlet height; see section 2.2).

Mean Seasonal Variations of the daily minimum and maximum ^{222}Rn activity concentrations. Ratios between modelled simulations and observations

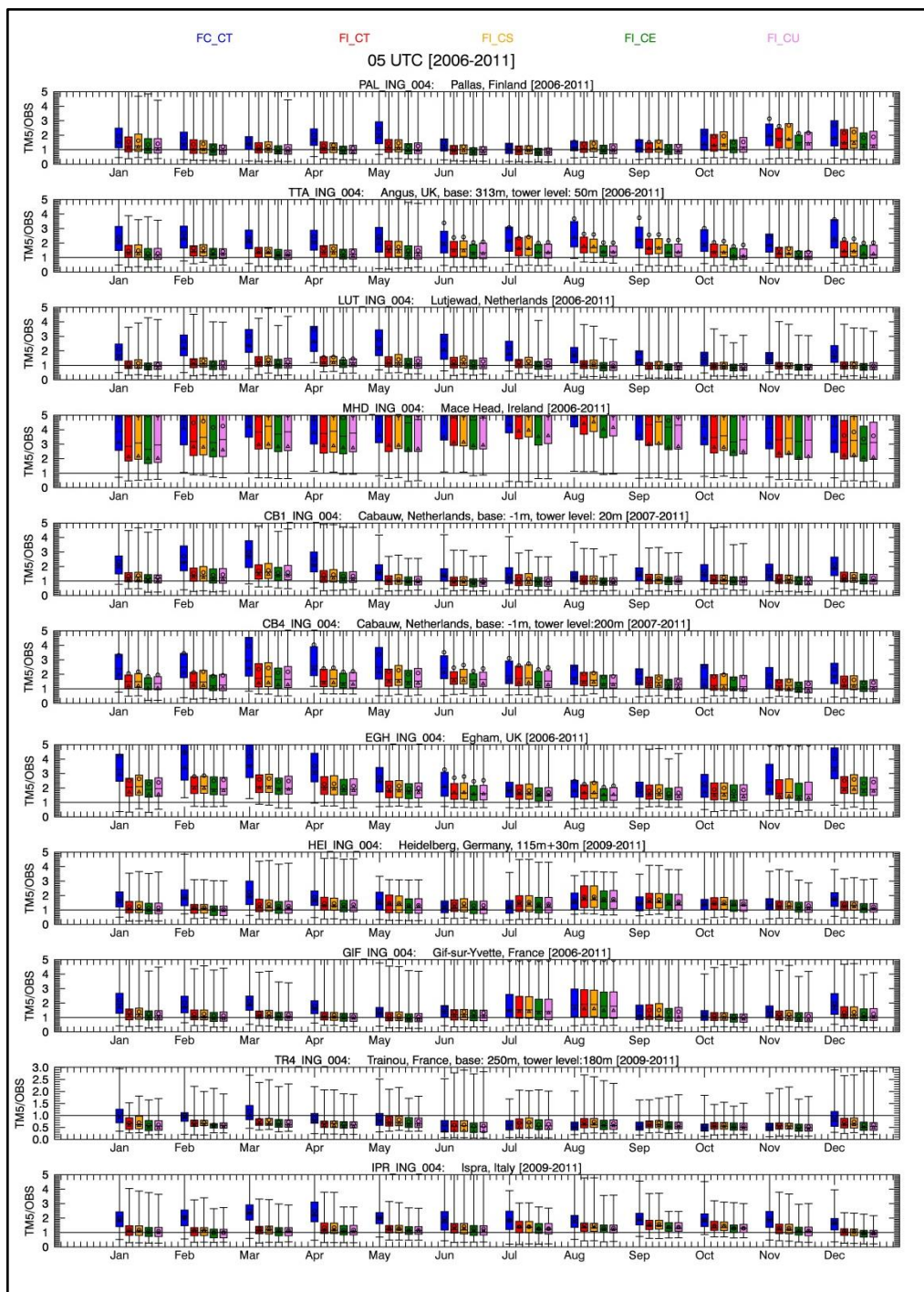


Figure S29: Seasonal variations of the ratios of daily maximum simulated activity radon concentrations versus observations at INGOS sites illustrated at 05 UTC and for 2006-2011 period. The minimum and maximum values of each data set are shown. The boxes are delimited by the 25% and 75% percentiles. The median values are given by the horizontal line in the boxes. The mean values are given by the open circles. The observed radon activity concentrations are in blank. The model simulations (in colors) are obtained from constant emissions (blue box: FC_CT) and from INGOS emission maps (red box: F_INGOS_D; orange box: FI_CS; green box: FI_CE, and violet box: FI_CU). Triangles stand for the ratios between the mean of model data and the mean of observed data

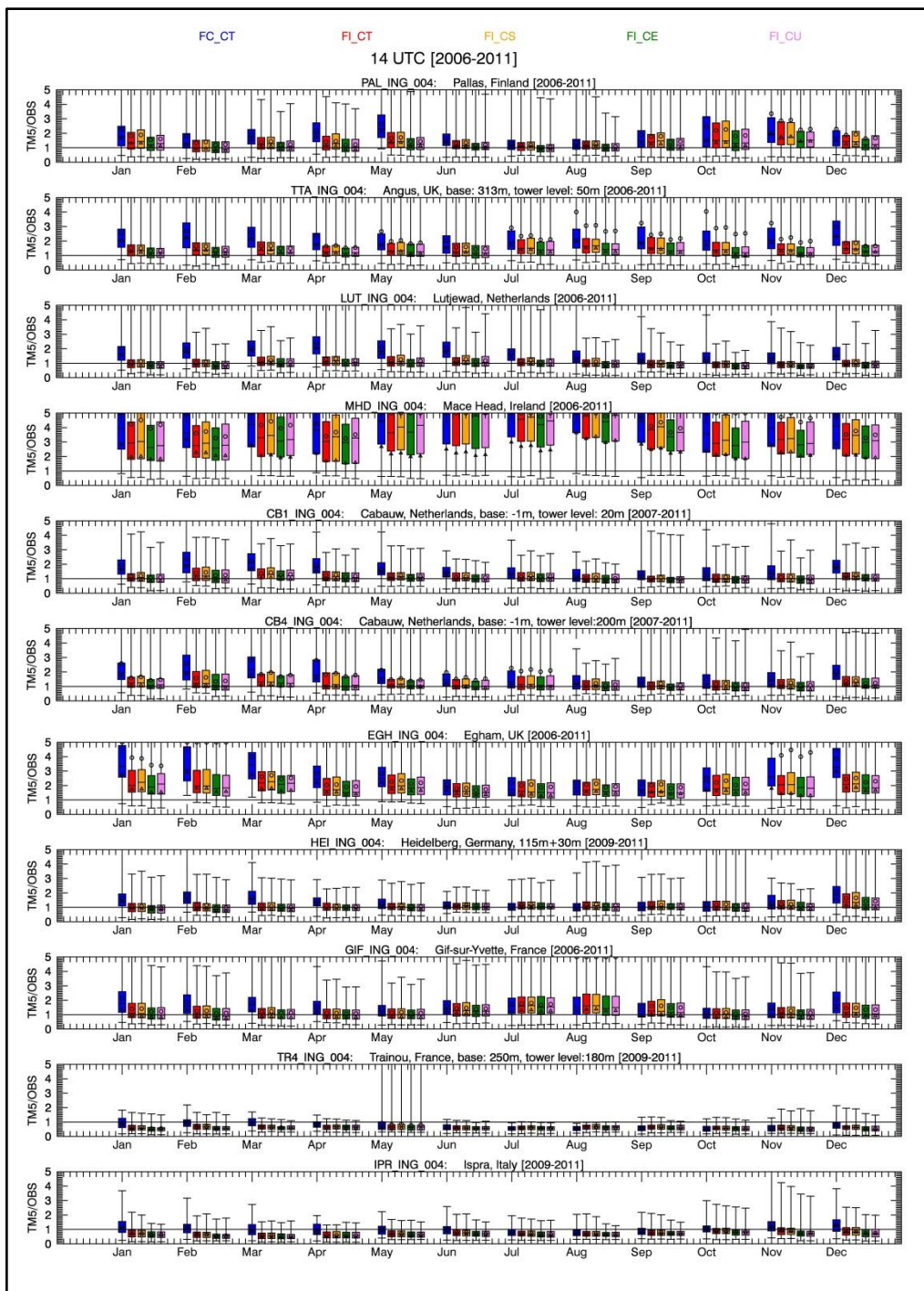


Figure S30: As Figure S29, but at 14 UTC illustrating the daily minimum radon activity concentrations.

**Sensitivity of simulated radon activity concentrations
to the “updated slope treatment”, the new convection
scheme and their coupling**

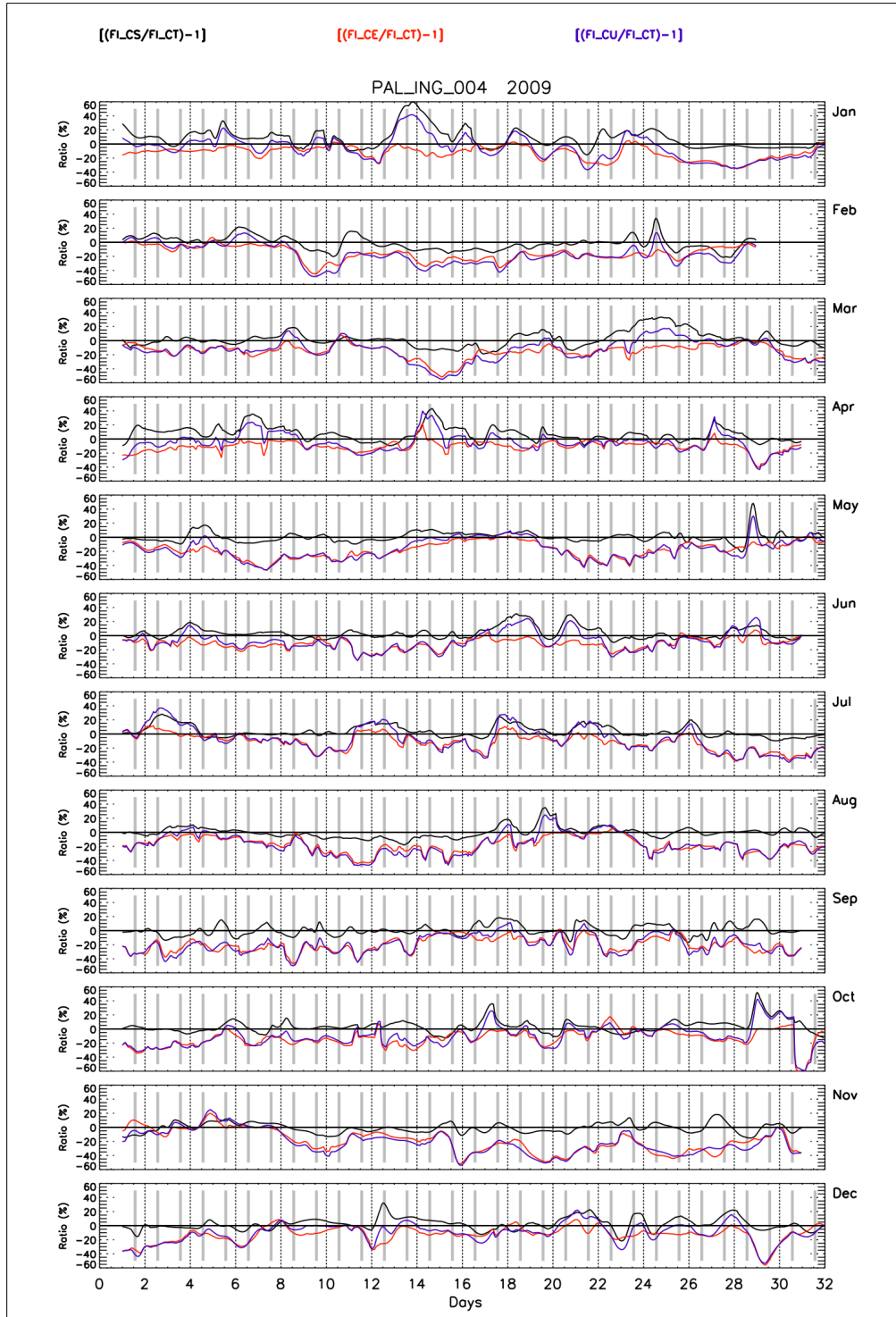


Figure S31: Sensitivity of the model to both “updated slope” and new convection scheme and their coupling for 2009. The simulated radon activity concentrations are normalized by the simulations by using the default convection and slope treatment scheme. The grey bars describe the time window used for the TM5-4DVAR inversion system (12:00-15:00 LT). For the model acronyms on the top, see page 26 in this document or Section in the paper. The simulations are for Pallas (PAL) station

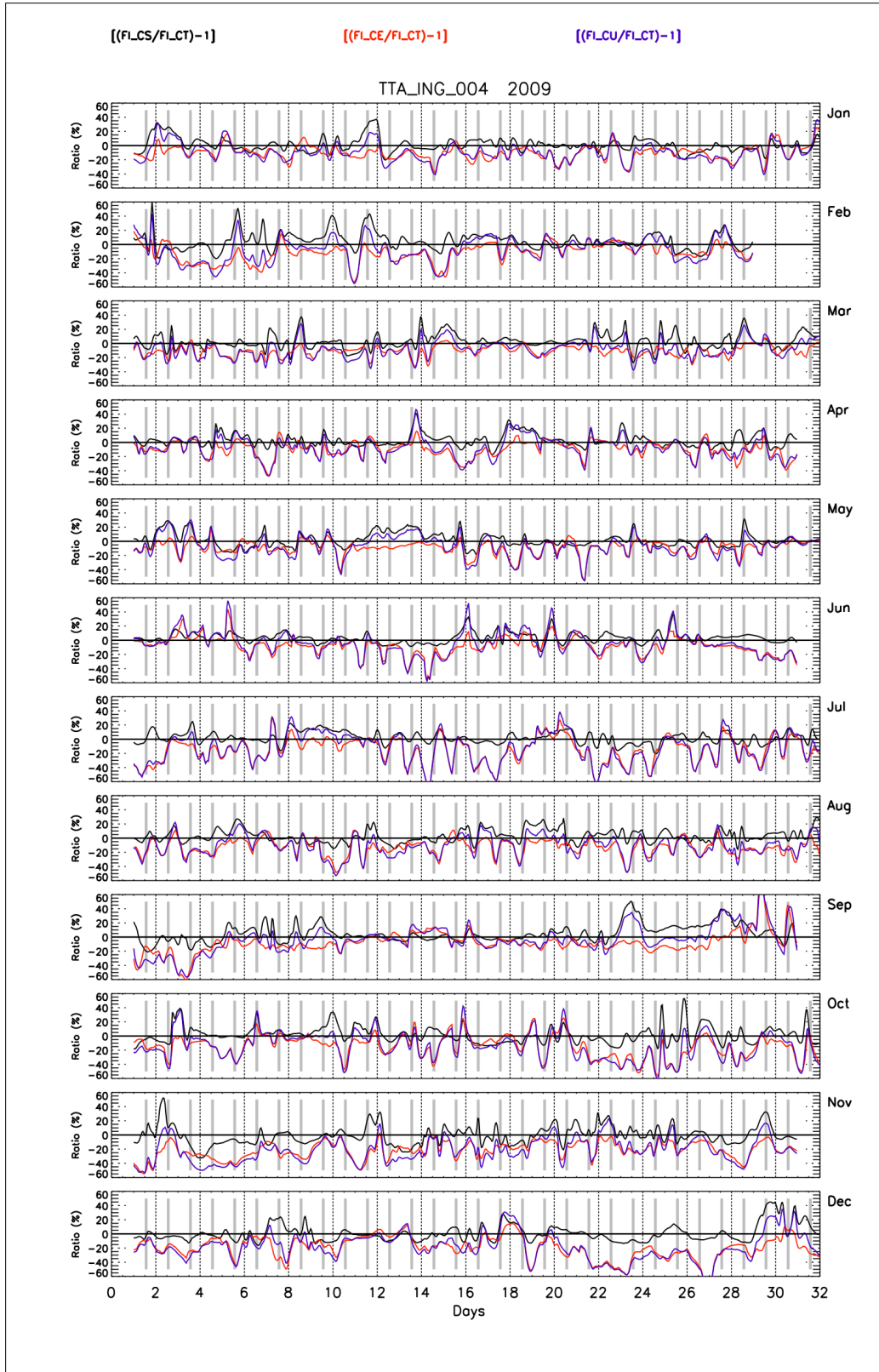


Figure S32: As Figure S31, but for the InGOS station Angus (TTA)

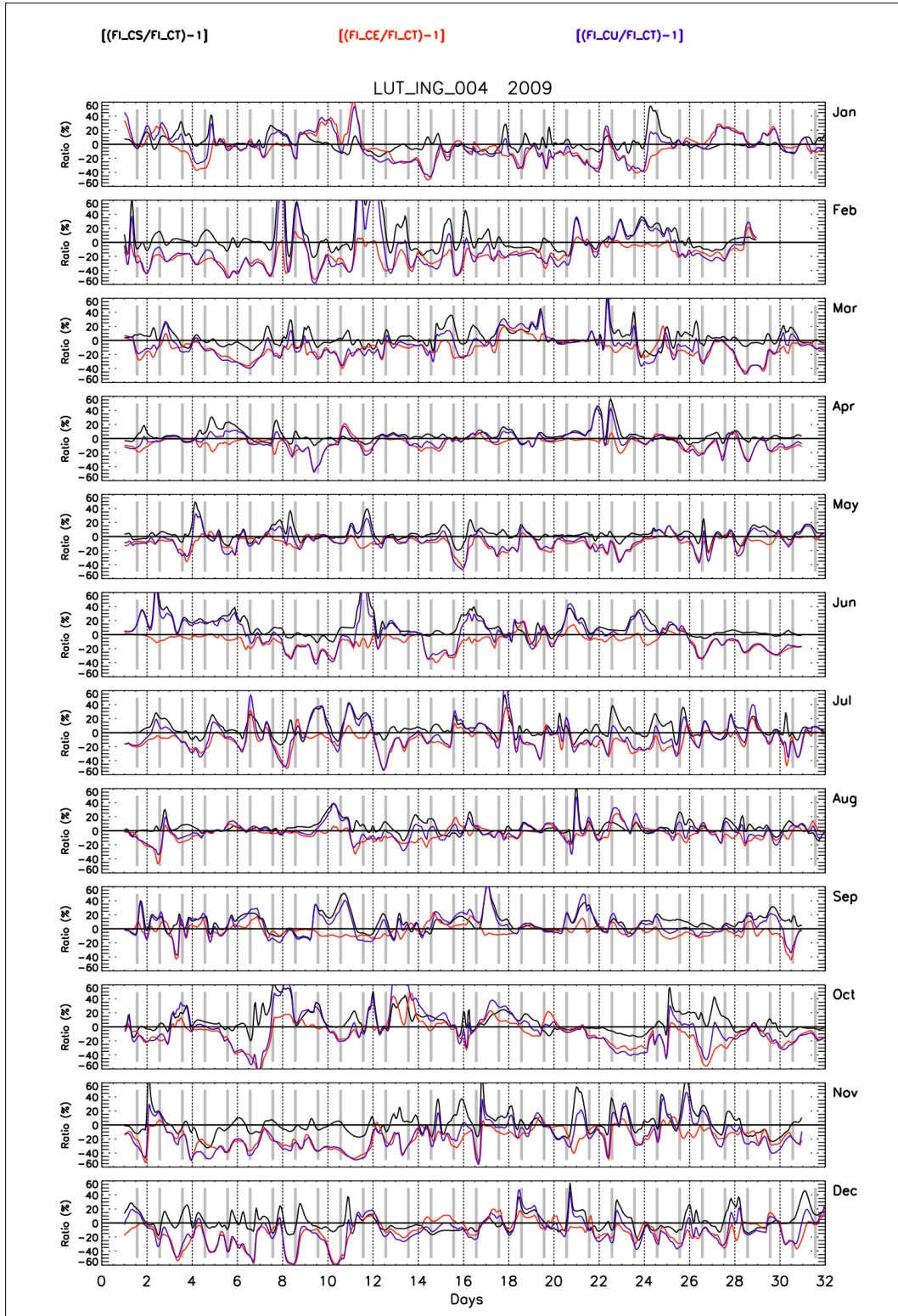


Figure S33: As Figure S31, but for the InGOS station Lutjewad (LUT)

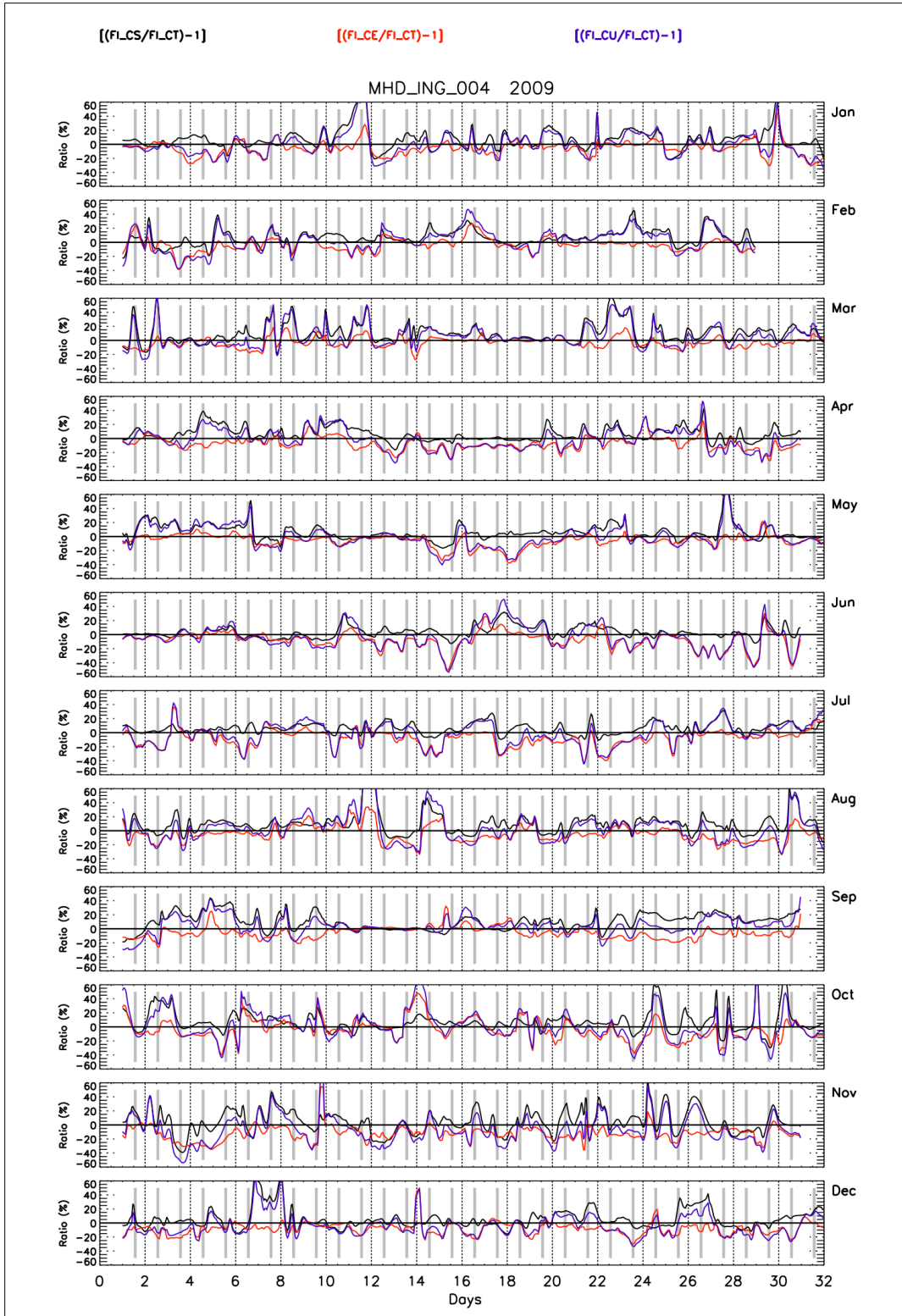


Figure S34: As Figure S31, but for the InGOS station Mace Head (MHD)

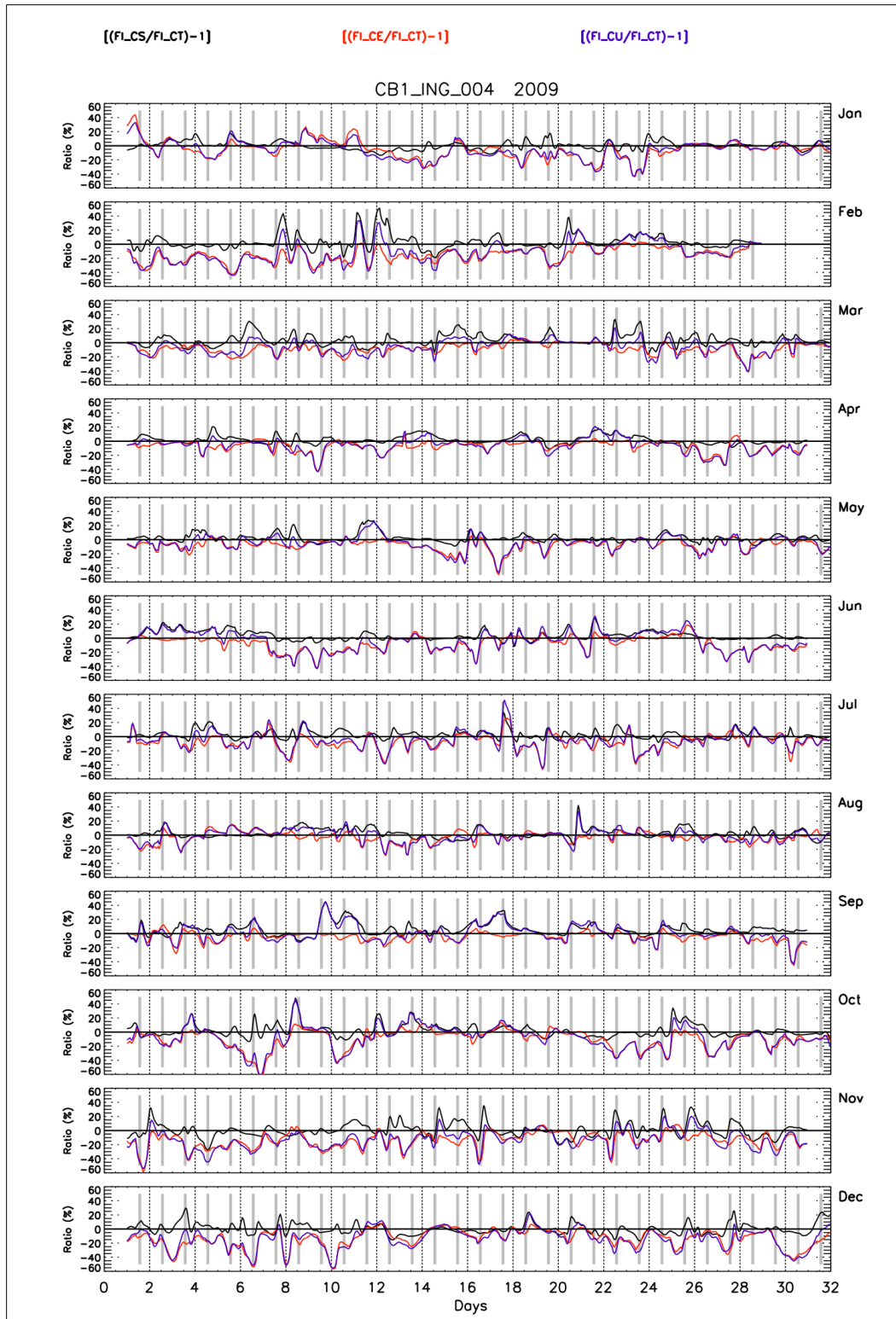


Figure S35: As Figure S3&, but for the InGOS station Cabauw (CB1)

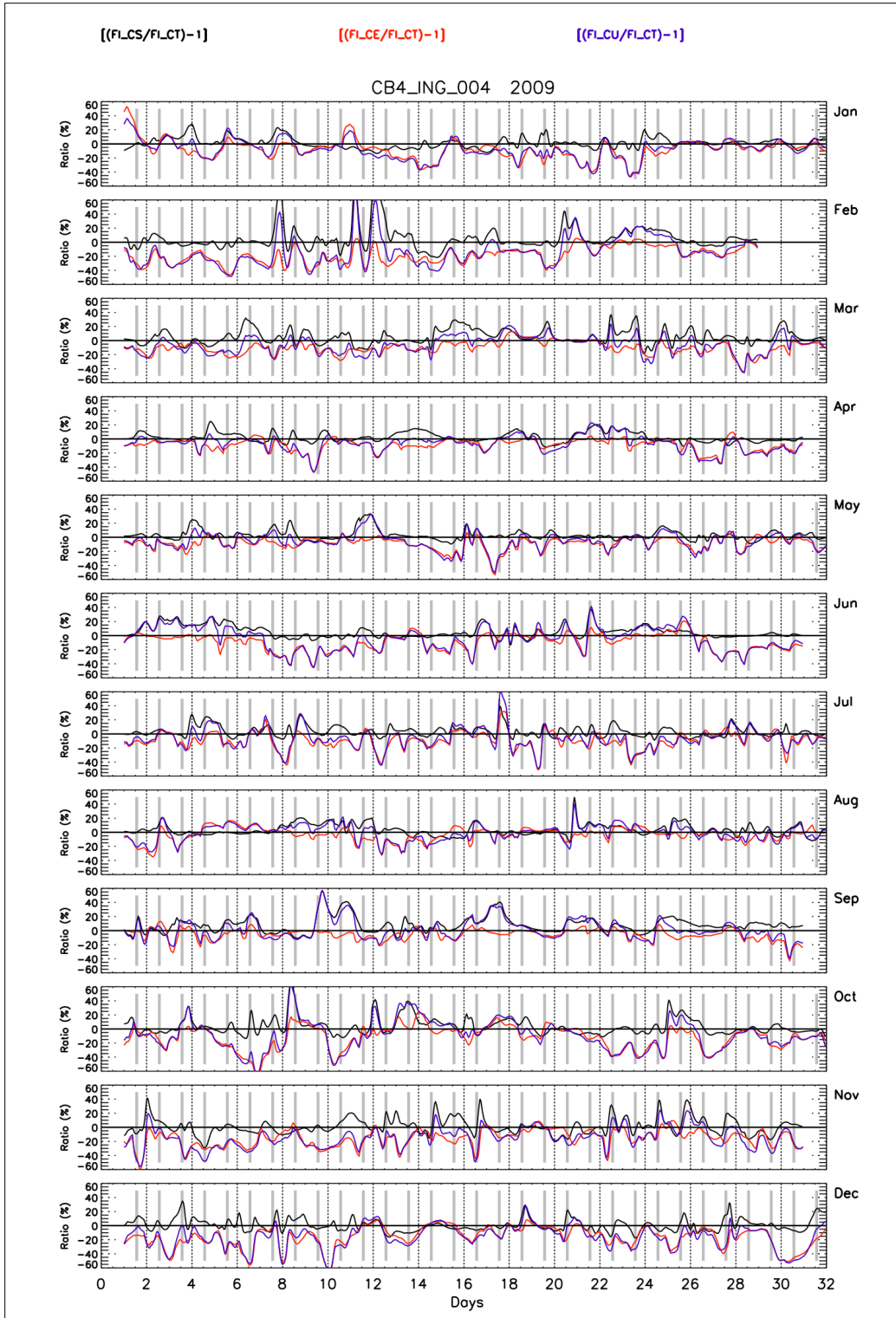


Figure S3-: As Figure S31, but for the InGOS station Cabauw (CB4)

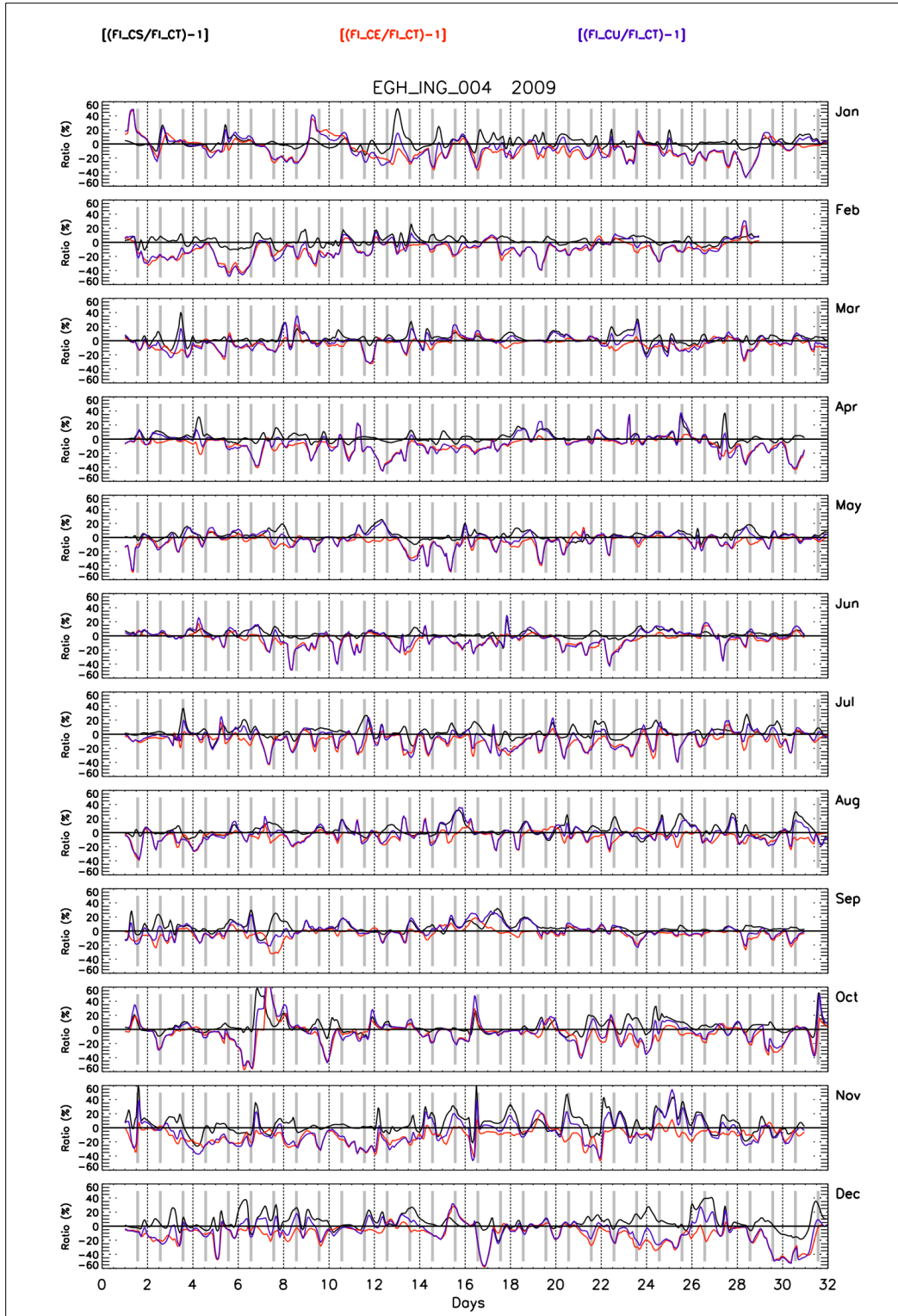


Figure S37: As Figure S31, but for the InGOS station Egham (EGH)

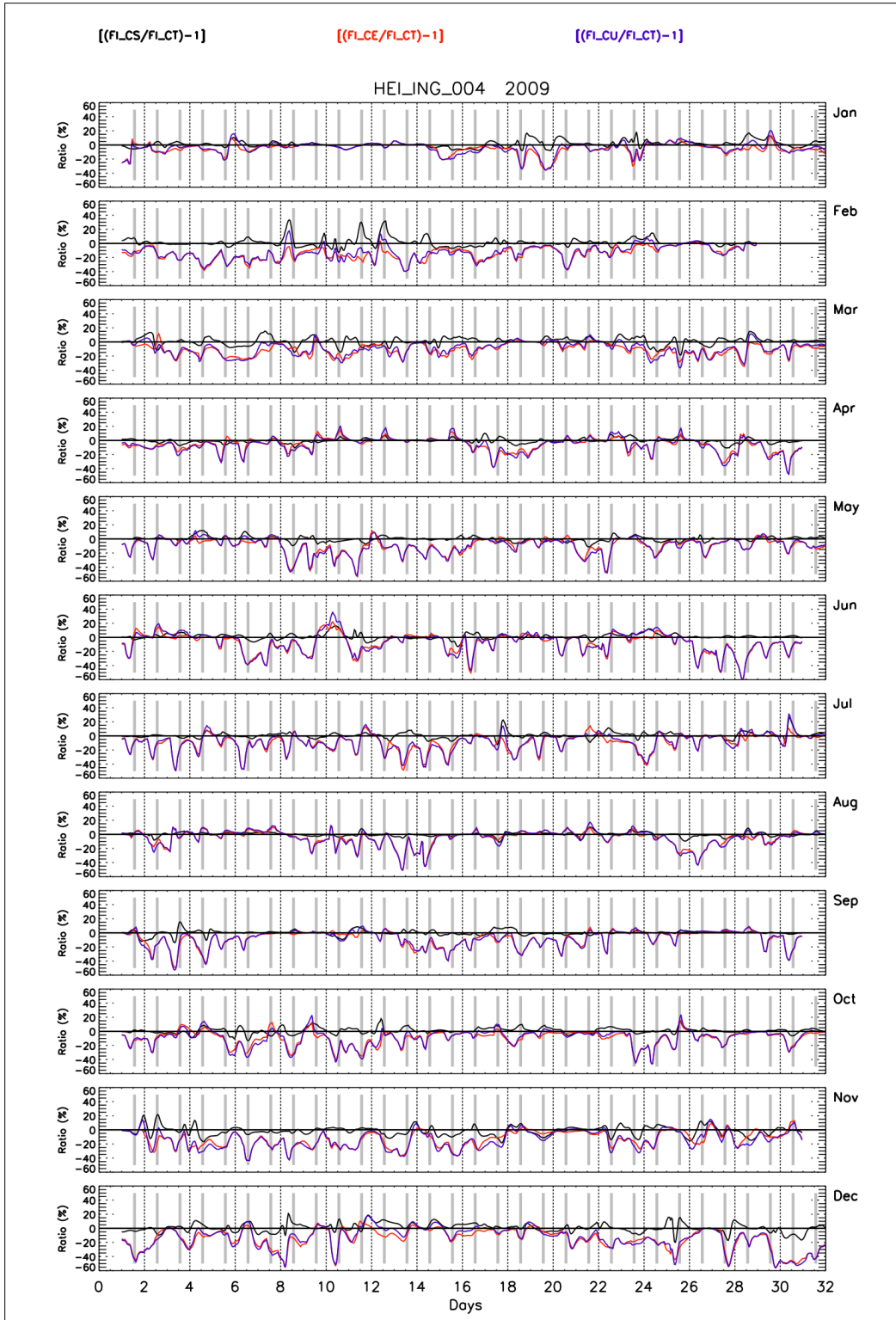


Figure S38: As Figure S31, but for the InGOS station Heidelberg (HEI)

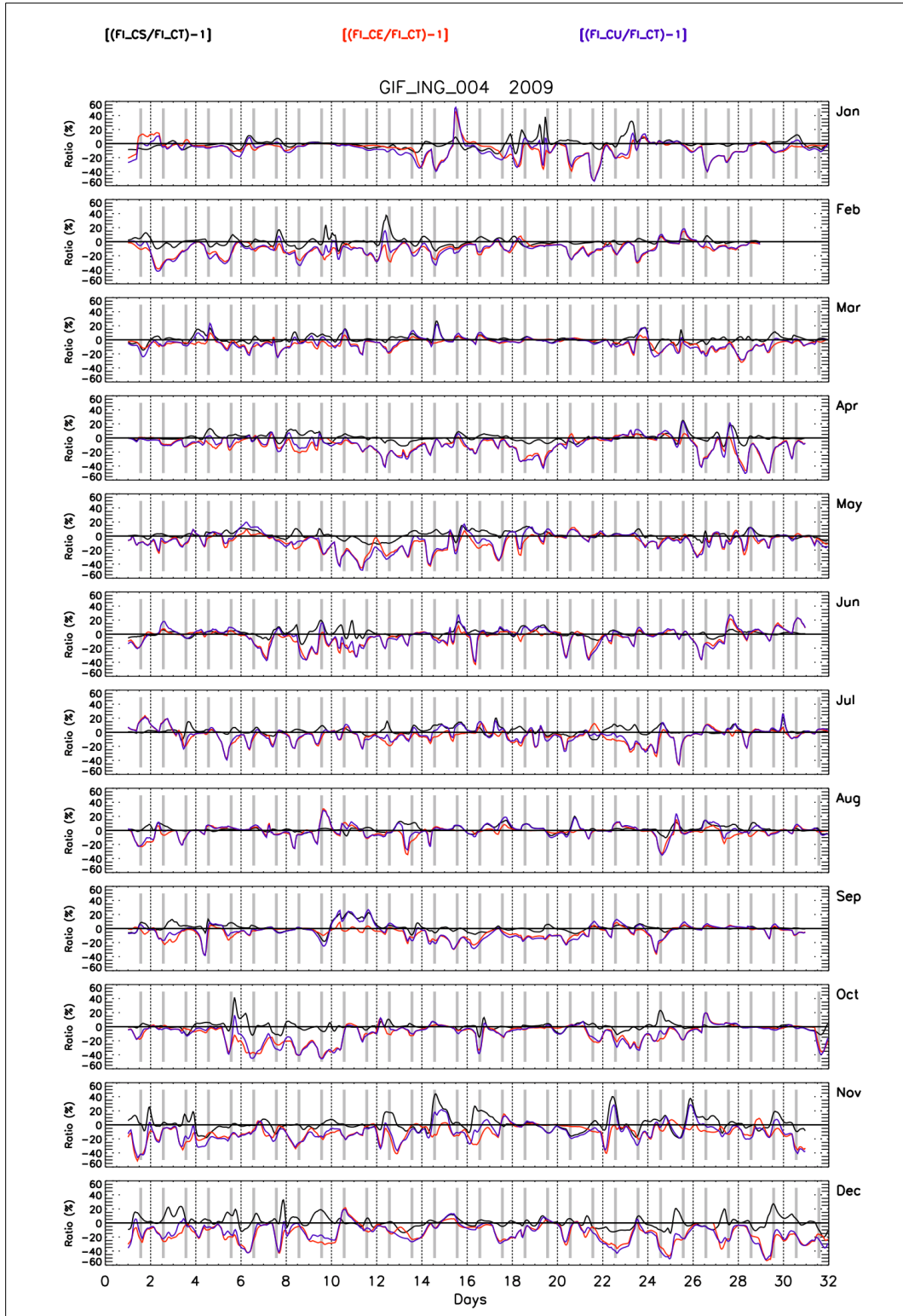


Figure S39: As Figure S31, but for the InGOS station Gif sur Yvette (GIF)

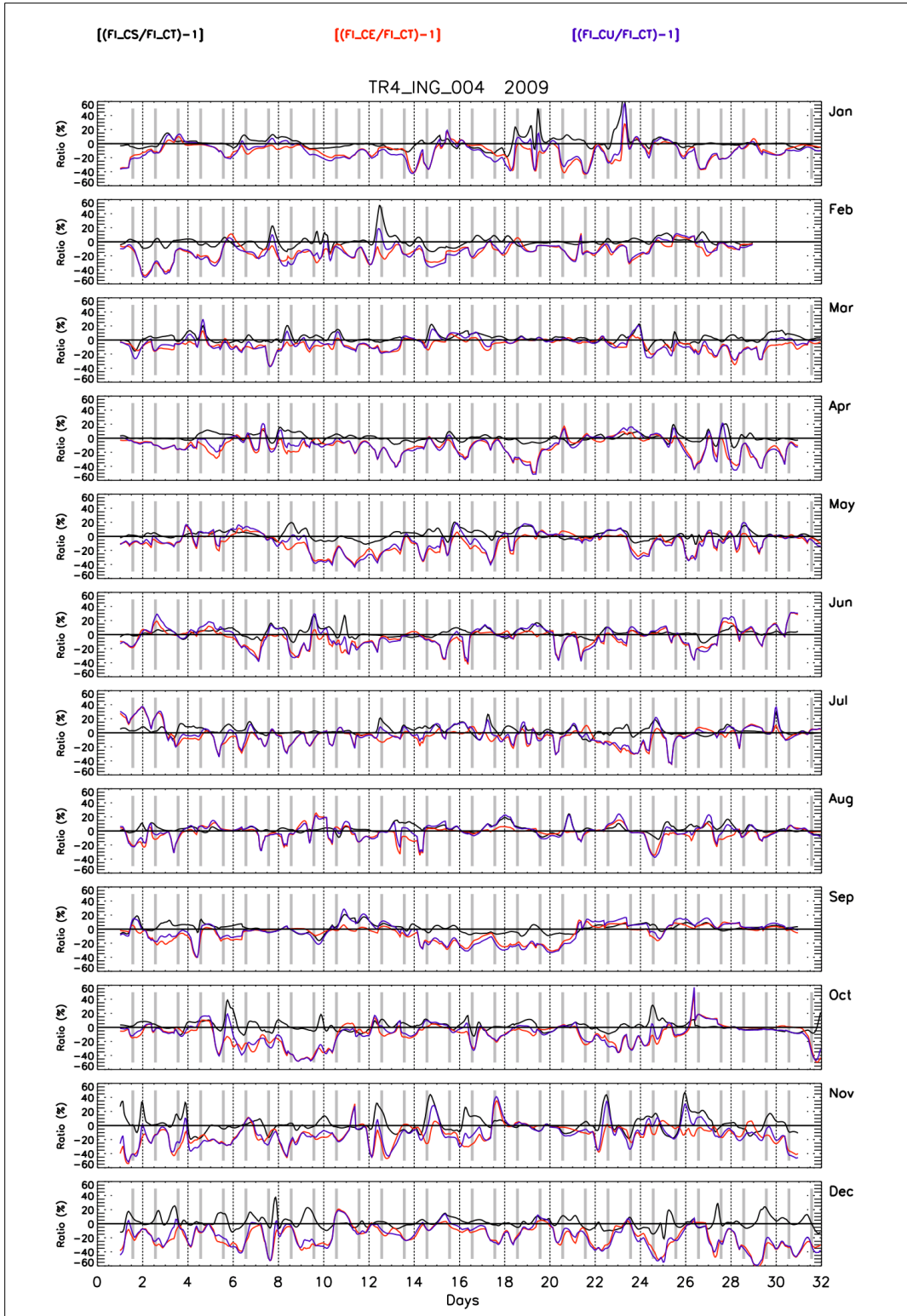


Figure S40: As Figure S31 but for the InGOS station Trainou (TR4)

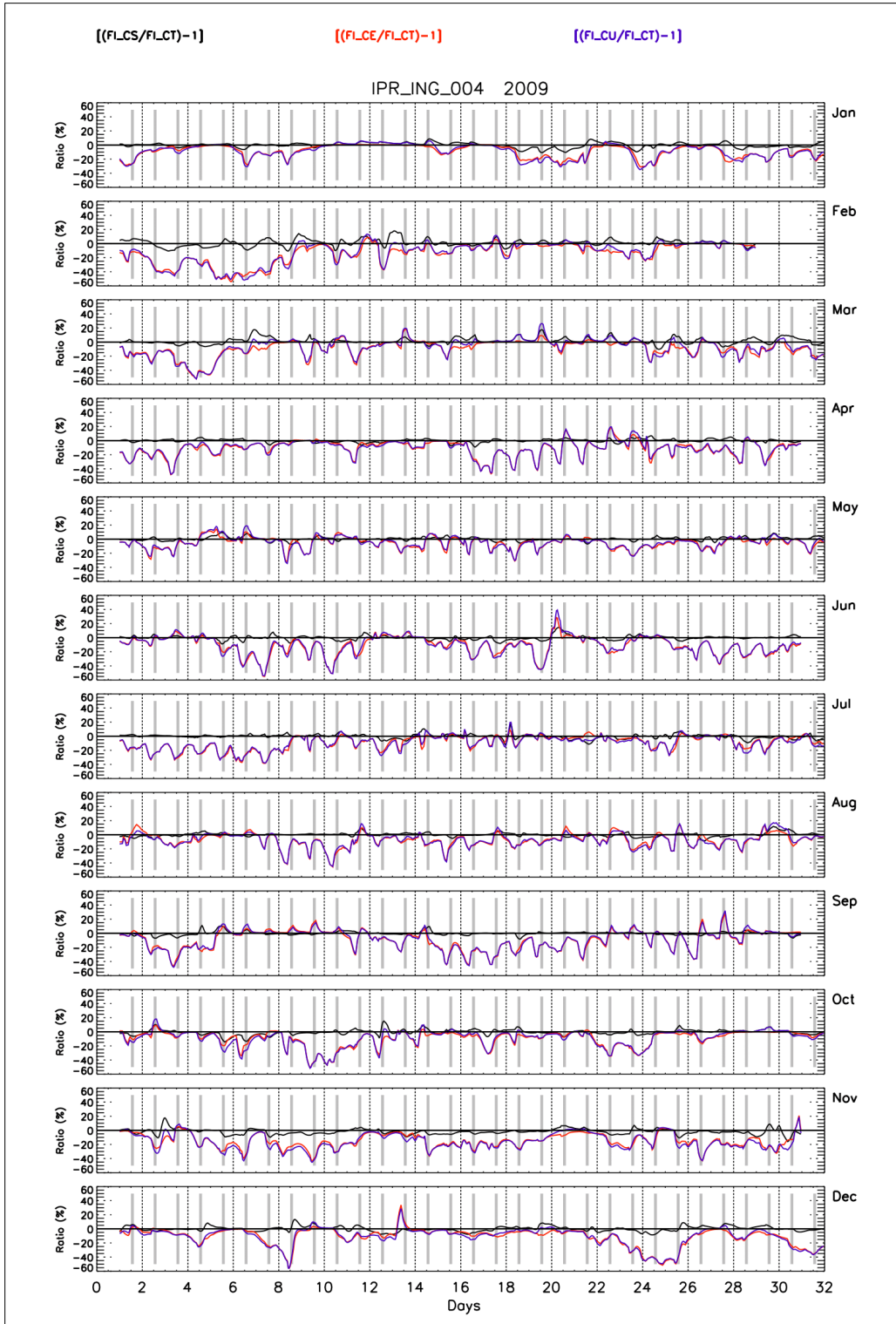


Figure S41: As Figure S31, but for the InGOS station Ispra (IPR)

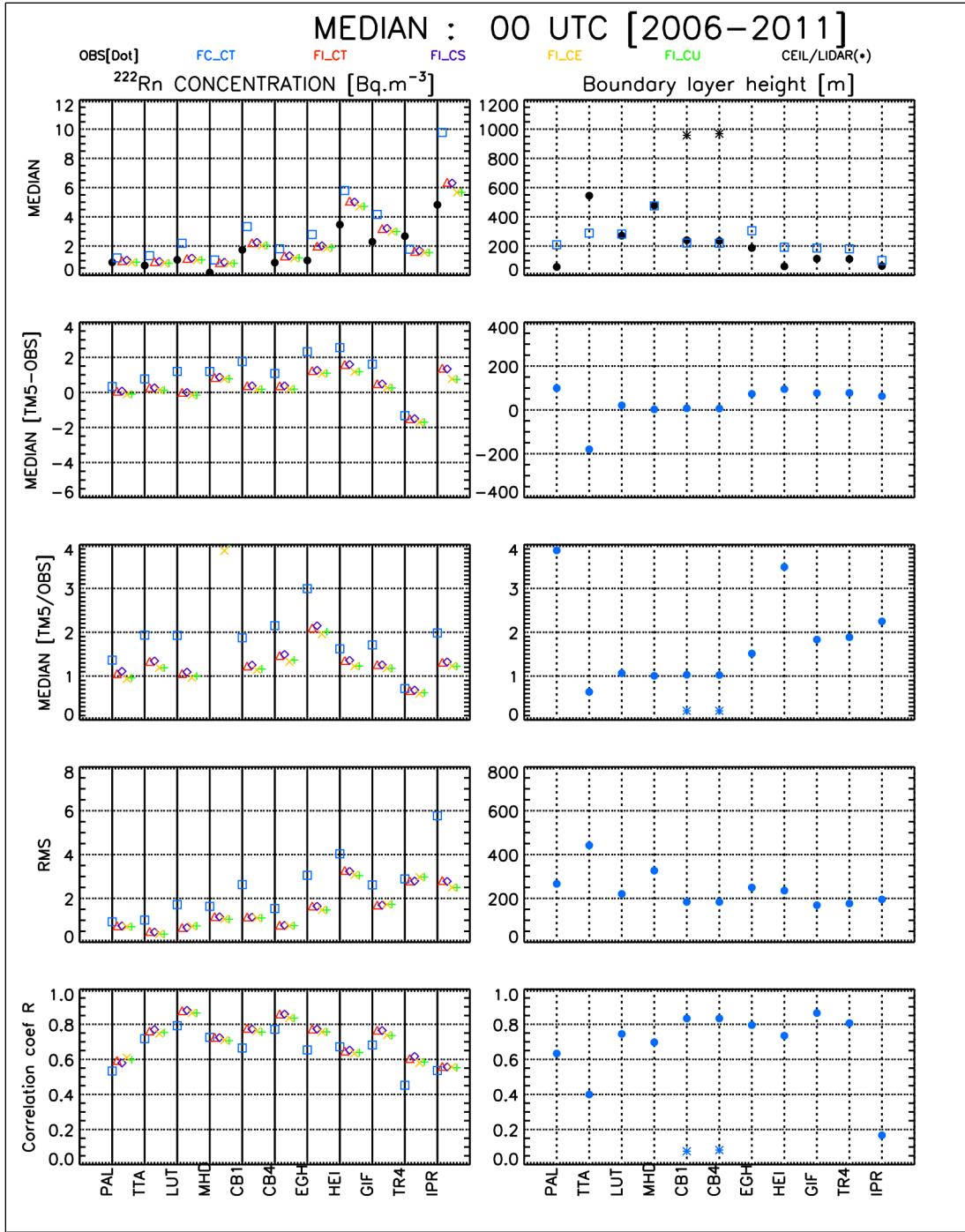


Figure S42: Statistics on radon activity concentrations (observed (●) and simulations (different model set ups shown at the top of the graphs)) for each station are shown on the left hand side. The derived statistics using observed IGRA (●) and ceilometer (CEIL)/LIDAR (*) boundary layer heights are presented on the right hand side. The data at 00 UTC are considered. The acronyms of the stations are indicated in x-axis with relevant names given in Table 1. For the median and RMS values, the unit of the y-axis is given on the top of the relevant graphs. The different model settings are given on the top of the graphs (See Section 4.2 of the text for details). The number of pair of data for each station is larger than 500.

Correlation between radon activity concentration and the inverse of boundary layer height

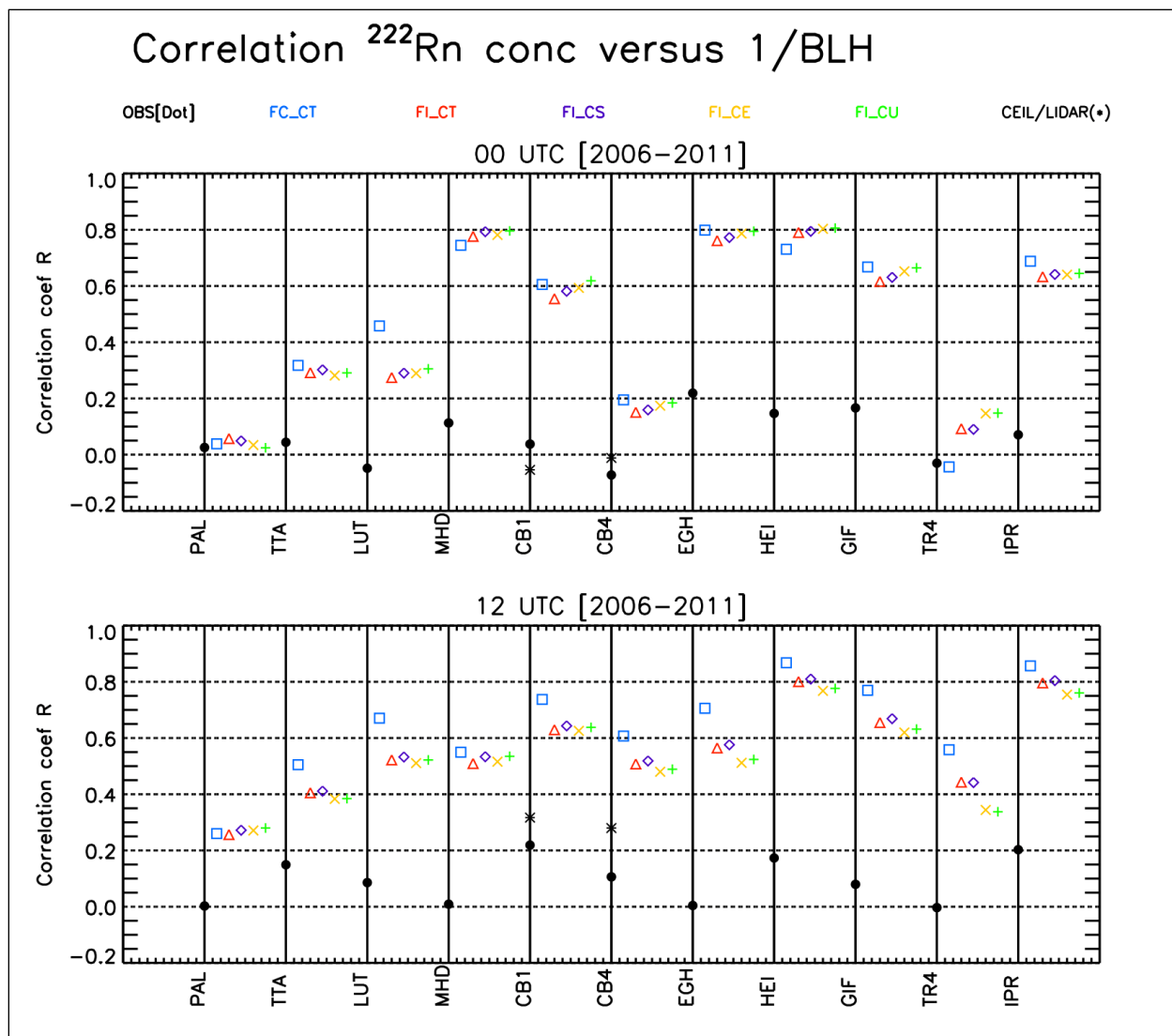


Figure S43: Linear correlation coefficients between observed radon concentrations and the inverse of the boundary layer heights from IGRA (●) and ceilometer (CEIL)/LIDAR (*) measurements and for each InGOS station. The same calculations are performed for the different model set ups (acronyms shown at the top of the graphs) and by using the model boundary layer heights. The results at 00 (top) and 12 UTC (bottom) are shown. The acronyms of the stations are indicated in x-axis with relevant names given in Table 1. The different model acronyms are defined in Section 4 of the text. The number of pair of data for each station used to compute the linear correlation coefficients R are larger than 500.

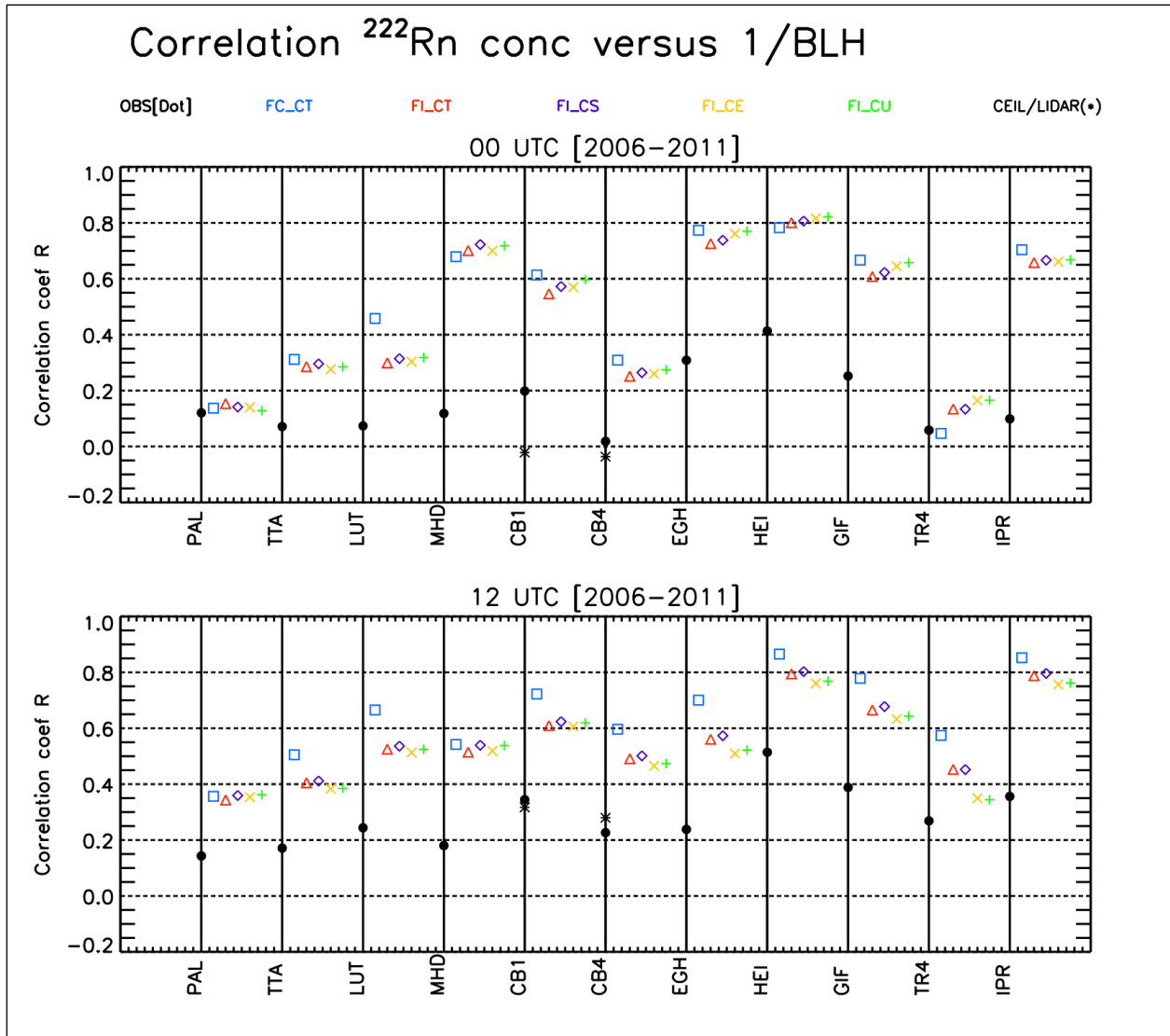


Figure S44: As Figure S43, but for cases with boundary layer heights greater than 50 m. The number of pair of data used to compute the linear correlation coefficients are larger than 400.