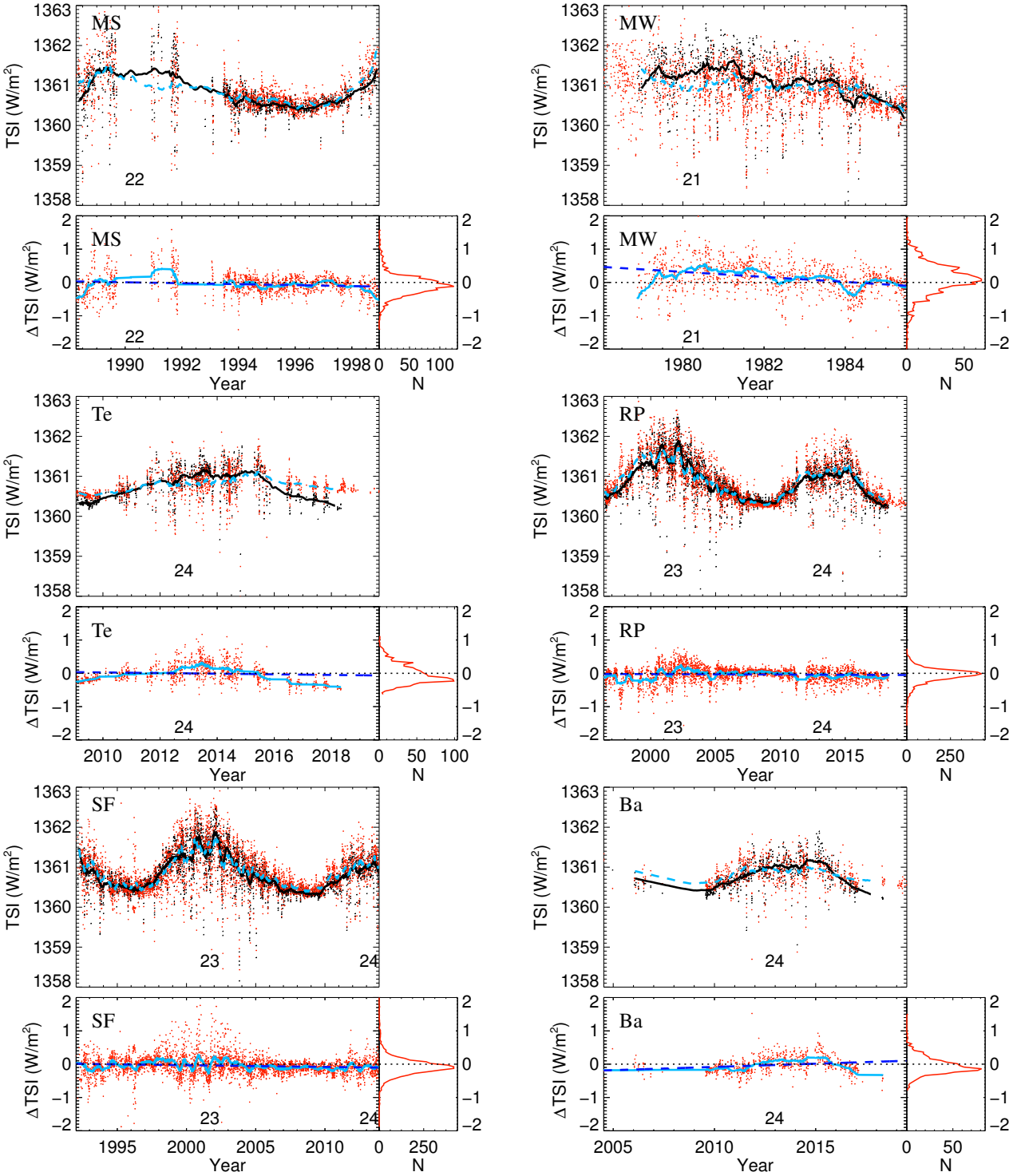


Fig. 11. *Upper part of each panel:* TSI reconstructions from Ca II K observations using the reconstructed TSI series from MD1 Ca II K data as the reference. Daily values from the MS, MW, Te, RP, SF, and Ba datasets are shown as red dots and the corresponding 81-day running means as dashed blue lines. For comparison, the PMOD irradiance composite series is overplotted (black dots for daily values and the solid black line for the 81-day running means), which was used as the reference for the reconstructed series from MD1 Ca II K data. The running means have been computed considering only days on which both the reconstructions and the PMOD series were available. *Lower left part of each panel:* difference between the PMOD composite and the reconstructed TSI (red dots for daily values and solid light blue for 81-day running means). The dashed blue line is a linear fit to the residuals. The horizontal black dotted line marks the zero difference. *Lower right part of each panel:* distribution of the residuals in bins of 0.05 Wm^{-2}. The numbers in the bottom part of each panel indicate the solar cycle number, which are placed roughly at the maximum of each cycle.

We used the images from the Mount Wilson (MW) and Meudon (MD1) archives to reconstruct the TSI over the period after 1978, when we can compare the outcome to direct TSI measurements. We showed that inconsistencies within the archives can distort the results. However, if the inconsistencies are identified, then such data can still be used to recover irradiance

variations sufficiently accurately. Thus, identifying and potentially accounting for such inconsistencies and discontinuities will be the main challenge for reconstructions of irradiance from historical archives. Once such issues are better understood and taken into account for the available archives processed by Chatzistergos et al. (2020c), we will use them for the reconstruction of irradiance over the 20th century.

In this paper we focused on presenting results for TSI; however the model also produces the spectrally resolved solar irradiance (solar spectral irradiance, SSI) over 115–160 000 nm. Future work aiming at the reconstruction of the past irradiance variations from historical and modern Ca II K data using the method described in this paper will include both TSI and SSI.

Finally, we used the TSI reconstruction from the MD1 archive (which were photographic prior to 2002 and CCD-based afterwards) as a reference for reconstructions from other archives. We found that the quality of the reconstructions remained comparable to that when the PMOD TSI was used as a reference. This is extremely important, considering that many historical datasets do not overlap with direct irradiance measurements and thus optimising the free parameter would not be possible otherwise.

In summary, we have shown that historical Ca II K data are a viable source of information on the facular and network contribution to solar irradiance variations. The availability of such data for over a century will allow irradiance variations to be reconstructed based on independent data sources for sunspots and faculae for a considerably longer period of time than has been possible so far.

Acknowledgements. The authors thank the observers at the Baikal, Big Bear, Brussels, Calern, Kanzelhöhe, Mauna Loa, Mees, Meudon, Mt Wilson, Rome, San Fernando, and Teide sites. We thank Isabelle Buale for all her efforts to digitise the Meudon photographic archive. We also thank the anonymous referee for encouraging and constructive suggestions that helped us to improve the presentation of our work. T. C. acknowledges funding from the European Union's Horizon 2020 research and Innovation program under grant agreement No 824135 (SOLARNET). This work was supported by the Italian MIUR-PRIN grant 2017 "Circumterrestrial Environment: Impact of Sun–Earth Interaction" (grant 2017APKP7T), by the German Federal Ministry of Education and Research (Project No. 01LG1909C), and by the BK21 plus program through the National Research Foundation (NRF) funded by the Ministry of Education of Korea. This research has made use of NASA's Astrophysics Data System.

References

Ambelu, T., Falayi, E. O., Elemo, E. O., & Oladosu, O. 2011, Latin-Amer. J. Phys. Educ., 5
Arlt, R., Leussu, R., Giese, N., Mursula, K., & Usoskin, I. G. 2013, MNRAS, 433, 3165
Arlt, R., Senthamizh Pavai, V., Schmiel, C., & Spada, F. 2016, A&A, 595, A104
Babcock, H. W., & Babcock, H. D. 1955, ApJ, 121, 349
Ball, W. T., Unruh, Y. C., Krivova, N. A., et al. 2012, A&A, 541, A27
Bethge, C., Peter, H., Kentischer, T. J., et al. 2011, A&A, 534, A105
Brueckner, G. E., & Bartoe, J.-D. F. 1983, ApJ, 272, 329
Carrasco, V. M. S., Vaquero, J. M., Arlt, R., & Gallego, M. C. 2018, Sol. Phys., 293, 102
Carrasco, V. M. S., Vaquero, J. M., Gallego, M. C., et al. 2019, MNRAS, 485, L53
Carrasco, V., Nogales, J. M., Vaquero, J. M., Chatzistergos, T., & Ermolli, I. 2021a, J. Space Weather Space Clim., 11, 51
Carrasco, V. M. S., Vaquero, J. M., & Gallego, M. C. 2021b, PASJ, 73, 747
Chapman, G. A., Cookson, A. M., & Dobias, J. J. 1996, J. Geophys. Res., 101, 13541
Chapman, G. A., Cookson, A. M., & Dobias, J. J. 1997, ApJ, 482, 541
Chapman, G. A., Cookson, A. M., & Preminger, D. G. 2012, Sol. Phys., 276, 35
Chapman, G. A., Cookson, A. M., & Preminger, D. G. 2013, Sol. Phys., 283, 295
Chatzistergos, T. 2017, Analysis of historical solar observations and long-term changes in solar irradiance, PhD Thesis (Uni-edition)
Chatzistergos, T., Ermolli, I., Solanki, S. K., & Krivova, N. A. 2016, in Coimbra Solar Physics Meeting: Ground-based Solar Observations in the Space Instrumentation Era, eds. I. Dorotovic, C. E. Fischer, & M. Temmer, ASP Conf. Ser., 504, 227
Chatzistergos, T., Usoskin, I. G., Kovaltsov, G. A., Krivova, N. A., & Solanki, S. K. 2017, A&A, 602, A69
Chatzistergos, T., Ermolli, I., Krivova, N. A., & Solanki, S. K. 2018a, in Long-term Datasets for the Understanding of Solar and Stellar Magnetic Cycles, eds. D. Banerjee, J. Jiang, K. Kusano, & S. Solanki (Cambridge, UK: Cambridge University Press), IAU Symp., 340, 125
Chatzistergos, T., Ermolli, I., Solanki, S. K., & Krivova, N. A. 2018b, A&A, 609, A92
Chatzistergos, T., Ermolli, I., Falco, M., et al. 2019a, in Il Nuovo Cimento, 42C, 5
Chatzistergos, T., Ermolli, I., Krivova, N. A., & Solanki, S. K. 2019b, A&A, 625, A69
Chatzistergos, T., Ermolli, I., Solanki, S. K., et al. 2019c, Sol. Phys., 294, 145
Chatzistergos, T., Ermolli, I., Solanki, S. K., et al. 2019d, A&A, 626, A114
Chatzistergos, T., Ermolli, I., Giorgi, F., Krivova, N. A., & Puiu, C. C. 2020a, J. Space Weather Space Clim., 10, 45
Chatzistergos, T., Ermolli, I., Krivova, N. A., & Solanki, S. K. 2020b, J. Phys.: Conf. Ser., 1548, 012007
Chatzistergos, T., Ermolli, I., Krivova, N. A., et al. 2020c, A&A, 639, A88
Chatzistergos, T., Krivova, N. A., Ermolli, I., et al. 2021, in ESSOAr, San Francisco, 3
Choudhary, D. P., Cadavid, A. C., Cookson, A., & Chapman, G. A. 2020, Sol. Phys., 295, 15
Clette, F., & Lefèvre, L. 2016, Sol. Phys., 291, 2629
Clette, F., & Lefèvre, L. 2018, Proc. Int. Astron. Union, 13, 17
Coddington, O., Lean, J. L., Pilewskie, P., Snow, M., & Lindholm, D. 2016, Bull. Am. Meteorol. Soc., 97, 1265
Criscuoli, S., Penza, V., Lovric, M., & Berrilli, F. 2018, ApJ, 865, 22
Dasi-Espuig, M., Jiang, J., Krivova, N. A., & Solanki, S. K. 2014, A&A, 570, A23
Dasi-Espuig, M., Jiang, J., Krivova, N. A., et al. 2016, A&A, 590, A63
Dewitte, S., & Nevens, S. 2016, ApJ, 830, 25
Dewitte, S., Crommelynck, D., & Joukoff, A. 2004, J. Geophys. Res. (Space Phys.), 109, A02102
Ermolli, I., Caccin, B., Centrone, M., & Penza, V. 2003, Mem. Soc. Astron. It., 74, 603
Ermolli, I., Criscuoli, S., Centrone, M., Giorgi, F., & Penza, V. 2007, A&A, 465, 305
Ermolli, I., Criscuoli, S., & Giorgi, F. 2011, Contrib. Astron. Obs. Skalnate Pleso, 41, 73
Ermolli, I., Matthes, K., Dudok de Wit, T., et al. 2013, Atmos. Chem. Phys., 13, 3945
Fligge, M., & Solanki, S. K. 1998, A&A, 332, 1082
Fligge, M., Solanki, S. K., & Unruh, Y. C. 2000, A&A, 353, 380
Fontenla, J. M., & Landi, E. 2018, ApJ, 861, 120
Fontenla, J., White, O. R., Fox, P. A., Avrett, E. H., & Kurucz, R. L. 1999, ApJ, 518, 480
Foukal, P. 1998, Geophys. Res. Lett., 25, 2909
Foukal, P. 2002, Geophys. Res. Lett., 29, 2089
Foukal, P. 2012, Sol. Phys., 279, 365
Foukal, P., & Lean, J. 1986, ApJ, 302, 826
Foukal, P., & Lean, J. 1988, ApJ, 328, 347
Foukal, P. V., Mack, P. E., & Vernazza, J. E. 1977, ApJ, 215, 952
Fröhlich, C. 2006, Space Sci. Rev., 125, 53
Fröhlich, C. 2013, Space Sci. Rev., 176, 237
Fröhlich, C., Crommelynck, D. A., Wehrli, C., et al. 1997, Sol. Phys., 175, 267
Golovko, A. A., Golubeva, E. M., Grechnev, V. V., et al. 2002, Solar Variability: From Core to Outer Frontiers (ESA Publications Division), 506, 929
Gray, L. J., Beer, J., Geller, M., et al. 2010, Rev. Geophys., 48, 4001
Gueymard, C. A. 2018, Adv. Sol. Resour. Assess. Forecasting, 168, 2
Haigh, J. D. 2007, Liv. Rev. Sol. Phys., 4, 2
Hayakawa, H., Besser, B. P., Iju, T., et al. 2020a, ApJ, 890, 98
Hayakawa, H., Clette, F., Horaguchi, T., et al. 2020b, MNRAS, 492, 4513
Hayakawa, H., Iju, T., Murata, K., & Besser, B. P. 2021, ApJ, 909, 194
Hickey, J. R., Stowe, L. L., Jacobowitz, H., et al. 1980, Science, 208, 281
Hirtenfellner-Polanec, W., Temmer, M., Pötzi, W., et al. 2011, Cent. Eur. Astrophys. Bull., 35, 205
Intergovernmental Panel on Climate Change 2013, Climate change 2013: the physical science basis: Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (New York, NY: Cambridge University Press) oCLC: ocn892580682
Intergovernmental Panel on Climate Change 2021, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth

Assessment Report of the Intergovernmental Panel on Climate Change, eds. V. Masson-Delmotte, P. Zhai, A. Pirani, et al. (Cambridge University Press)
Johannesson, A., Marquette, W., & Zirin, H. 1995, Sol. Phys., 161, 201
Johannesson, A., Marquette, W. H., & Zirin, H. 1998, Sol. Phys., 177, 265
Kahil, F., Riethmüller, T. L., & Solanki, S. K. 2017, ApJS, 229, 12
Kahil, F., Riethmüller, T. L., & Solanki, S. K. 2019, A&A, 621, A78
Kopp, G. 2016, J. Space Weather Space Clim., 6, A30
Kopp, G., Lawrence, G., & Rottman, G. 2005, in The Solar Radiation and Climate Experiment (SORCE), eds. G. Rottman, T. Woods, & V. George (New York: Springer), 129
Kopp, G., Boyle, B., Heuerman, K., et al. 2013, AGU Fall Meeting Abstracts, 51, GC51C
Kopp, G., Krivova, N., Wu, C. J., & Lean, J. 2016, Sol. Phys., 291, 2951
Kren, A. C., Pilewskie, P., & Coddington, O. 2017, J. Space Weather Space Clim., 7, A10
Krivova, N. A. 2018, Climate Changes in the Holocene (CRC Press), 107
Krivova, N. A., & Solanki, S. K. 2004, A&A, 417, 1125
Krivova, N. A., Solanki, S. K., Fligge, M., & Unruh, Y. C. 2003, A&A, 399, L1
Krivova, N. A., Balmaceda, L., & Solanki, S. K. 2007, A&A, 467, 335
Krivova, N. A., Solanki, S. K., & Wenzler, T. 2009a, Geophys. Res. Lett., 36, L20101
Krivova, N. A., Solanki, S. K., Wenzler, T., & Podlipnik, B. 2009b, J. Geophys. Res. (Atmos.), 114
Krivova, N. A., Vieira, L. E. A., & Solanki, S. K. 2010, J. Geophys. Res. (Space Phys.), 115, 12112
Krivova, N., Solanki, S., & Unruh, Y. 2011, J. Atmos. Sol.-Terr. Phys., 73, 223
Kurucz, R. L. 1970, SAO Special Report, 309
Kurucz, R. L. 1993, in International Astronomical Union, Colloquium No. 138, held in Trieste, Italy, July 1992, eds. M. dworetsky, F. Castelli, & R. Faraggiana (San Francisco: Astronomical Society of the Pacific), Astron. Soc. Pac., 44, 87
Kurucz, R. L. 2005, Mem. Soc. Astron. It. Suppl., 8, 14
Lean, J. L. 2018, Earth Space Sci., 5, 133
Lean, J. L., & Repoff, T. P. 1987, J. Geophys. Res.: Atmos., 92, 5555
Lean, J. L., & Skumanich, A. 1983, J. Geophys. Res., 88, 5751
Lean, J. L., Cook, J., Marquette, W., & Johannesson, A. 1998, ApJ, 492, 390
Lefebvre, S., Ulrich, R. K., Webster, L. S., et al. 2005, Mem. Soc. Astron. It., 76, 862
Leighton, R. B., Noyes, R. W., & Simon, G. W. 1962, ApJ, 135, 474
Lockwood, M., Owens, M. J., Barnard, L., & Usoskin, I. G. 2016, Sol. Phys., 291, 2829
Loukitcheva, M., Solanki, S. K., & White, S. M. 2009, A&A, 497, 273
Malherbe, J.-M., & Dalmasse, K. 2019, Sol. Phys., 294, 52
Mandal, S., Krivova, N. A., Solanki, S. K., Sinha, N., & Banerjee, D. 2020, A&A, 640, A78
Matthes, K., Funke, B., Andersson, M. E., et al. 2017, Geosci. Model Dev., 10, 2247
Mauceri, S., Coddington, O., Lyles, D., & Pilewskie, P. 2019, Sol. Phys., 294, 160
Meftah, M., Corbard, T., Hauchecorne, A., et al. 2018, A&A, 616, A64
Morrill, J. 2005, Mem. Soc. Astron. It., 76, 850
Morrill, J. S., Floyd, L., & McMullin, D. 2011a, Sol. Phys., 269, 253
Morrill, J. S., Floyd, L., Ulrich, R., Weaver, S., & McMullin, D. 2011b, Sol. Phys., 270, 109
Naqvi, M. F., Marquette, W. H., Tritschler, A., & Denker, C. 2010, Astron. Nachr., 331, 696
Norris, C. M., Beeck, B., Unruh, Y. C., et al. 2017, A&A, 605, A45
Oster, L., Schatten, K. H., & Sofia, S. 1982, ApJ, 256, 768
Pap, J. M., Marquette, W. H., & Donnelly, R. F. 1991, Adv. Space Res., 11, 271
Penza, V., Caccin, B., Ermolli, I., Centrone, M., & Gomez, M. T. 2003, in Solar Variability as an Input to the Earth's Environment, ESA Spec. Pub., 535, 299
Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, Sol. Phys., 275, 3
Pilewskie, P., Kopp, G., Richard, E., et al. 2018, Proceedings from the 20th EGU General Assembly held 4–13 April, 2018 in Vienna, Austria, 20, 5527
Preminger, D. G., Walton, S. R., & Chapman, G. A. 2002, J. Geophys. Res. (Space Phys.), 107, 1354
Puiu, C. C. 2019, Master's Thesis, Sapienza - University of Rome, Italy
Rast, M. P., Ortiz, A., & Meisner, R. W. 2008, ApJ, 673, 1209
Schatten, K. H., Miller, N., Sofia, S., Endal, A. S., & Chapman, G. 1985, ApJ, 294, 689
Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, Sol. Phys., 275, 207
Schmutz, W., Fehlmann, A., Finsterle, W., Kopp, G., & Thuillier, G. 2013, in AIP Conf. Ser., 1531, 624
Schou, J., Scherrer, P. H., Bush, R. I., et al. 2012, Sol. Phys., 275, 229
Schrijver, C. J., Cote, J., Zwaan, C., & Saar, S. H. 1989, ApJ, 337, 964
Shapiro, A. I., Solanki, S. K., Krivova, N. A., et al. 2017, Nat. Astron., 1, 612
Skumanich, A., Lean, J. L., Livingston, W. C., & White, O. R. 1984, ApJ, 282, 776
Solanki, S. K. 2003, A&ARv, 11, 153
Solanki, S. K., & Fligge, M. 1998, Geophys. Res. Lett., 25
Solanki, S. K., Schüssler, M., & Fligge, M. 2002, A&A, 383, 706
Solanki, S. K., Krivova, N. A., & Haigh, J. D. 2013, ARA&A, 51, 311
Steinegger, M., Vazquez, M., Bonet, J. A., & Brandt, P. N. 1996, ApJ, 461, 478
Tagirov, R. V., Shapiro, A. I., Krivova, N. A., et al. 2019, A&A, 631, A178
Unruh, Y. C., Solanki, S. K., & Fligge, M. 1999, A&A, 345, 635
Usoskin, I. G., Kovaltsov, G. A., & Chatzistergos, T. 2016a, Sol. Phys., 291, 3793
Usoskin, I. G., Kovaltsov, G. A., Lockwood, M., et al. 2016b, Sol. Phys., 291, 2685
Vaquero, J. M., Svalgaard, L., Carrasco, V. M. S., et al. 2016, Sol. Phys., 291, 3061
Vogler, F. L., Brandt, P. N., Otruba, W., & Hanslmeier, A. 2005, Hvar Obs. Bull., 29, 79
Vokhmyanin, M., Arlt, R., & Zolotova, N. 2020, Sol. Phys., 295, 39
Walton, S. R., Preminger, D. G., & Chapman, G. A. 2003, ApJ, 590, 1088
Wenzler, T., Solanki, S. K., & Krivova, N. A. 2005, A&A, 432, 1057
Wenzler, T., Solanki, S. K., Krivova, N. A., & Fröhlich, C. 2006, A&A, 460, 583
Wenzler, T., Solanki, S. K., & Krivova, N. A. 2009, Geophys. Res. Lett., 36, L11102
Willamo, T., Usoskin, I. G., & Kovaltsov, G. A. 2017, A&A, 601, A109
Willson, R. C. 1997, Science, 277, 1963
Willson, R. C., & Hudson, H. S. 1988, Nature, 332, 810
Willson, R. C., & Mordvinov, A. V. 2003, AGU Fall Meeting Abstracts, 31
Worden, J. R., Woods, T. N., & Bowman, K. W. 2001, ApJ, 560, 1020
Wu, C.-J., Krivova, N. A., Solanki, S. K., & Usoskin, I. G. 2018, A&A, 620, A120
Yeo, K. L., Solanki, S. K., & Krivova, N. A. 2013, A&A, 550, 95
Yeo, K. L., Krivova, N. A., Solanki, S. K., & Glassmeier, K. H. 2014, A&A, 570, A85
Yeo, K. L., Krivova, N. A., & Solanki, S. K. 2017a, J. Geophys. Res.: Space Phys., 122, 3888
Yeo, K. L., Solanki, S. K., Norris, C. M., et al. 2017b, Phys. Rev. Lett., 119
Yeo, K. L., Solanki, S. K., Krivova, N. A., et al. 2020, Geophys. Res. Lett., 47, e2020GL090243

Appendix A: Comparison between reconstructed TSI with RP data and various TSI series

Figure A.1 and A.2 show the difference between our reconstructed TSI with RP data and the various respective reference TSI series. The reconstructed TSI agrees quite well with the various TSI reference series. The trend of the residuals is generally flat or marginally decreasing, although for SORCE/TIM and the four empirical models (EMPIRE, NN-SIM, NRLTSI and PSUM), it is slightly increasing. We note that PSUM used exactly the same Ca II K data for their (empirical) reconstruction. The trend is somewhat stronger when we compare to SORCE/TIM, but this could also be, at least partly, due to the shorter period covered by this record. The marginally decreasing (increasing) trend means that our reconstructed TSI shows a marginally stronger (weaker) decline with time than the TSI series employed for comparison. Given that the differences are very small, all results appear consistent with each other. Only the ACRIM case is clearly different, with a strong decreasing trend in the residuals.

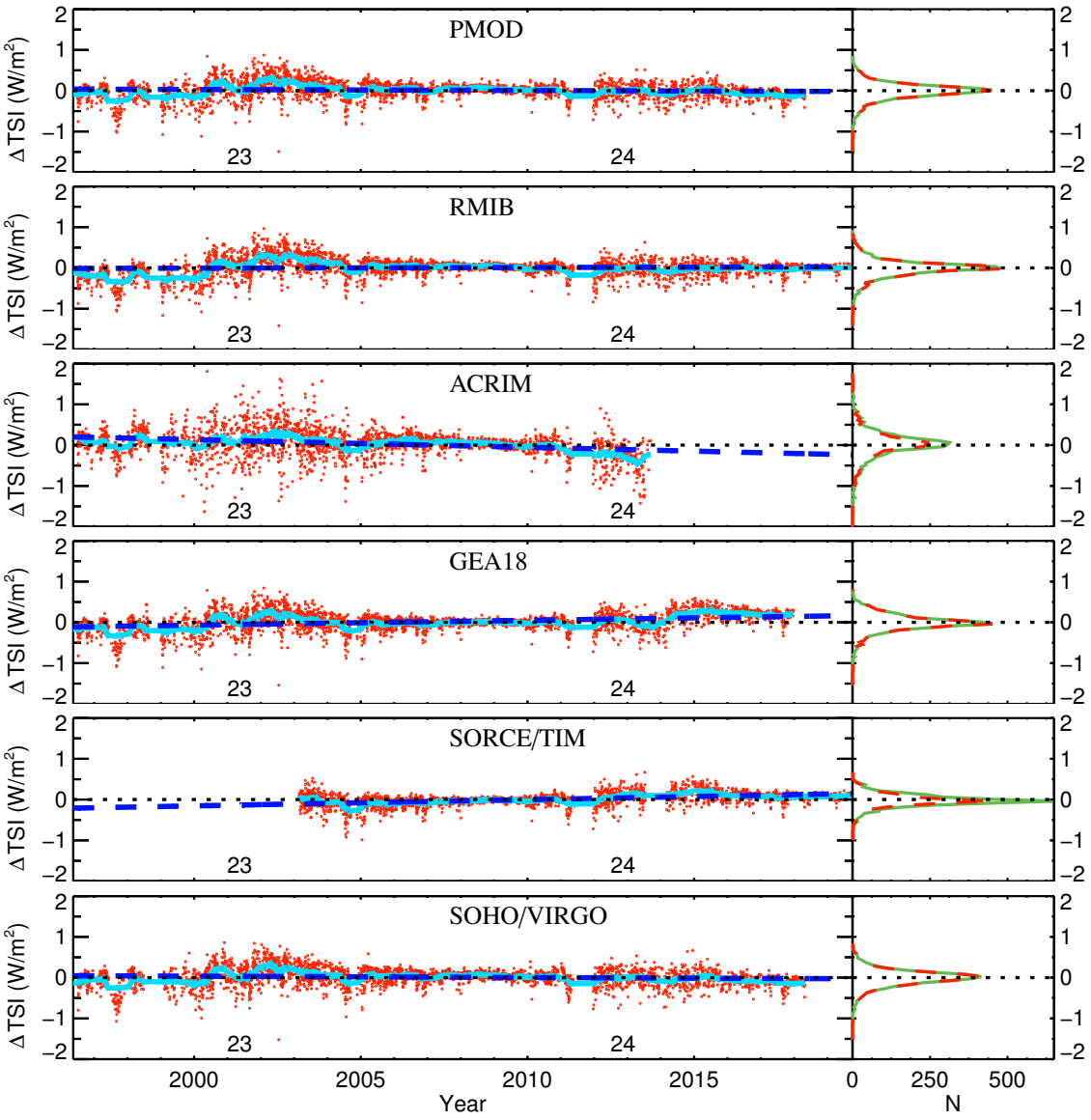


Fig. A.1. *Left:* Difference between the various TSI reference series and the TSI calculated from RP Ca II K data (red circles for daily values and light blue curve for 81-day running mean values) using the respective TSI reference series as a function of time. The TSI reference series used are PMOD, RMIB, ACRIM, GEA18, SORCE/TIM, and SOHO/VIRGO. Also shown is a linear fit to the residuals (dark blue dashed line). The horizontal dotted black line denotes the zero level difference. The numbers in the lower part of the panels denote the solar cycle number. *Right:* Distributions of the residuals in bins of 0.05 Wm^{-2} for the series shown in the left panels (red dashed). Also shown (in green) are the distributions normalised to the same number of days, namely that in the PMOD record.