1 **The potential value of early (1939-1967) upper-air data in atmospheric climate**

2 **reanalysis**

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20 **Abstract.** In recent years a number of reanalysis datasets have been published that

21 cover the past century or more, including the "Twentieth Century Reanalysis" 20CR

22 and the European Reanalysis of the twentieth century ERA-20C. These datasets are

23 widely used, showing the need for, and possible benefit of, reanalysis data products

24 designed for climate applications. The 20th century reanalyses so far have assimilated

25 only surface observations, and rely on independent estimates of monthly averaged

26 sea-surface temperatures and sea ice concentrations as boundary conditions. While

27 20CR uses only observations of surface and sea-level pressure, ERA-20C additionally

28 assimilates marine winds.

29 Here we describe an experimental reanalysis, referred to as ERA-PreSAT, which

30 covers the period 1939-1967 and also assimilates historical upper-air data.

Assessments of this data set including comparisons with independent data show that (1) temperature biases in the northern hemisphere are largely reduced compared to reanalyses that assimilate surface data only, (2) concentration of 1940s upper air data in the northern extratropics created a strong interhemispheric asymmetry which is likely not realistic, (3) the forecast skill in the northern hemisphere has increased substantially compared to reanalyses that assimilate surface data only, (4) day-to-day and (in the northern extratropics) month-to-month correlations with independent observations (of total column ozone, upper-air data) increase over time, (5) interannual variability is well captured in the reanalysis, (6) a signature of the stratospheric Quasi-Biennial Oscillation is present as far back as the 1940s and (7) tropical cyclones are not well represented.

The encouraging results from the experimental ERA-PreSAT reanalysis underline that early upper-air data greatly contribute to our knowledge on the troposphere and lower stratosphere over the 20th century.

1. Introduction

Reanalyses are increasingly used for studying historic weather events and to assess multi-decadal variability in weather and climate. In recent years a number of reanalysis data sets have been published that cover the past century or more.

Examples are the "Twentieth Century Reanalysis" 20CR and 20CRv2c from the National Oceanic and Atmospheric Administration Cooperative and the Institute for Research in Environmental Sciences (NOAA/CIRES-CDC), Compo et al. 2011, and the European Reanalysis of the twentieth century ERA-20C of the European Centre for Medium-Range Weather Forecasts (ECMWF), Poli et al. 2016. These datasets are widely used, showing the need for, and possible benefit of, atmospheric datasets that cover the early part of the instrumental period prior to the satellite-dominated modern era. So far, the 20th-century reanalyses have only assimilated surface observations, in addition to relying on boundary conditions derived from monthly estimates of sea-surface temperatures and sea-ice concentrations. 20CR and 20CRv2c assimilate surface and sea-level pressure, whereas ERA-20C additionally assimilates marine wind. The European projects ERA-CLIM and ERA-CLIM2, which have produced the ERA-20C and more recently the coupled CERA-20C reanalysis, additionally have recovered a large number of historical upper-air data from analogue media and

prepared them for use in reanalysis (Stickler et al. 2014a, 2014b). Together with the previously published The Comprehensive Historical Upper Air Network (CHUAN, Stickler et al. 2010), millions of upper-air profiles are available for the first half of the 20th century, which up to now however have only been used for validation purposes (e.g., Compo et al. 2011, Brönnimann et al. 2012b, Stickler et al. 2015).

Here we present an experimental reanalysis, termed ERA-PreSAT, covering the years 1939-1967, which uses the same assimilation system as ERA-20C but additionally assimilates upper-air observations from the CHUAN historical dataset (Stickler et al. 2010) supplemented by data from the upper-air archives at the National Center for Atmospheric Research (NCAR). We describe these datasets and how they were ingested into the assimilation system. Then we evaluate some aspects of the atmospheric energy cycle. We evaluate the reanalyses using additional independent historical upper air data from the ERA-CLIM dataset (Stickler et al. 2014) that had become available later. In addition, we also use historical observations of total column ozone to evaluate the ozone estimates in the reanalysis datasets (Brönnimann and Compo, 2012).

The paper is organised as follows. The ERA-PreSAT reanalysis system and the ingested historical upper-air data are described in Section 2. The specifications of the datasets for comparison are presented in Section 3, which include one reanalysis product and three different upper-air reconstructions. In Section 4 various aspects of ERA-PreSAT are validated and/or compared with these datasets. The paper ends with a discussion and conclusion (Section 5).

2. The ERA-PreSAT forecast and analysis system

The ERA-PreSAT model and data assimilation system is equal to that of ERA-20C (Poli et al. 2016). It is based on version 38r1 (ECMWF 2013) of the Integrated Forecasting System (IFS), but at a reduced resolution compared to the configuration used for operational weather forecasting at ECMWF. Horizontal spectral resolution is T159 (around 125km globally) and there are 91 levels in the vertical from the surface up to 1 Pa (around 80km) with roughly 51 in the troposphere, 31 in the stratosphere and 9 in the mesosphere. The atmosphere is two-way coupled with an ocean-wave model and a land-surface model. A detailed description of the IFS can be found at https://software.ecmwf.int/wiki/display/IFS/CY38R1+Official+IFS+Documentation.

97   Boundary conditions at the sea surface are obtained from the Hadley Centre Sea Ice

98   and Sea Surface Temperature dataset (HadISST) version 2.1.0.0 (Titchner and Rayner

99   2014; Kennedy et al. 2015), and radiative forcing is mostly obtained from CMIP5

100   recommended datasets. It has been shown (ERA-20CM, Hersbach et al. 2015) that a

101   model-only integration of these century-varying boundary conditions and forcing

102   adequately represent the main low-frequency variability of the 20th century

103   atmosphere (global warming, El Nino and La Nina events, the effect of major

104   volcanic eruptions), without the need for the assimilation of synoptic observations.

105   The analysis uses four-dimensional data assimilation (4D-Var), with two inner loops

106   at T95 horizontal resolution (around 210 km). Like ERA-20C, information on the

107   first-guess background errors is obtained from a previously produced ensemble of

108   20th-century data assimilations (Poli et al. 2015). Details can be found in Poli et al.

109   2016.

110

111   **2.1 The ERA-PreSAT observational data input**

112   Like ERA-20C, ERA-PreSAT assimilates surface pressure and sea-level pressure data

113   from the International Surface Pressure Databank (ISPD, Compo et al. 2010) version

114   3.2.6 and the International Comprehensive Ocean-Atmosphere Data Set (ICOADS,

115   Woodruff et al. 2011) version 2.5.1, as well as marine wind reports from ICOADS.

116   For details and information on the evolution over the 20th century of this observing

117   system see Poli et al. (2015, 2016).

118   In addition, ERA-PreSAT assimilates historical upper-air data from several sources:

119   the NCAR Upper Air Data Base Version 2 (UADB-2), the Comprehensive Historical

120   Upper-Air Network Version 1.7 (CHUANv1.7), as well as observations digitized

121   within the ERA-CLIM project (ERA-CLIM Version 0.9).

122   The UADB-2 data record contains the original records from a large number of

123   sources, has been uniformly formatted, metadata are standardized and measurement

124   units are consistent. A detailed description can be found at

125   http://rda/ucar.edu/datasets/ds370.1/UADB-Doc.pdf. ERA-PreSAT uses data from 44

126   sources, as displayed in Table 1 of the UADB document, with the exception of

127   sources 23 (China), 51 (NCDC 5420) and 151 (Russian Ships) which were not yet

128   available in the UADB-2 format at the time of the preparations for ERA-PreSAT.

4

129　The CHUAN v1.7 data record (Stickler et.al. 2010) comprises 3,987 station records

130　worldwide totalling about 16.4 million vertical profiles. It was also obtained from

131　NCAR as two separate sources: a raw ('r', source 31) and a corrected dataset ('c',

132　source 30). Both sets originate from the same data, though the latter contains some

133　corrections, such as RAOBCORE v1.3 (Haimberger, 2007) temperature bias

134　adjustments.

135　Note that CHUAN v1.7 also contains a large amount of data as monthly means for

136　which the underlying individual observation profiles are not available (Stickler et al.

137　2010), most notably over the USA in 1939-1944. These data may however be used for

138　independent validation.

139　The ERA-CLIM project included a large component of data rescue, inventoring,

140　locating, imaging, and digitizing observation records on paper or microfilm. The

141　ERA-PreSAT reanalysis uses a preliminary version of this data record (V0.9) and

142　misses several collections that have been added since.

143

144

145　**2.2 The assimilation of upper-air data in ERA-PreSAT**

146　At ECMWF, all upper-air data as described above were converted to the format used

147　at ECMWF for assimilating observations. Data were then presented to the

148　assimilation system as either wind profiles (so-called PILOT) or multivariate profiles

149　(so-called TEMP data: temperature and wind). Upper air humidity observations were

150　not assimilatedsince they were suspected to have large biases at this time, even at

151　heights below 300 hPa, as suggested by Dai et al. (2011). All observations were

152　submitted to the assimilation and there was no attempt to remove duplicates

153　beforehand (even though the CHUAN 'c' and 'r' data records contain duplicates). The

154　removal of duplicates was left to the screening part of the assimilation system, where

155　it could be decided which observations fit the background the best. This makes uses of

156　the prior assimilation, and enables to discard duplicate observations. Besides duplicate

157　removal, rejections are also made as a result of quality control, such as to screen data

158　that depart too much from the background model, or data that cannot be fitted well by

159　the analysis given all other constraints (e.g., an observation contradicting the others).

160　All upper-air data are assimilated using pressure as the vertical coordinate. In case this

161 information is missing, pressure is estimated using the height-pressure relationship of
162 the background, from the observation height, if available.

163 The observation errors represent the weight given to them in the assimilation, in
164 balance with the background errors. The upper-air temperature and wind observation
165 errors assumed in ERA-PreSAT follow the modern-day specifications. The assumed
166 wind observation error is 1.6 m/s from the surface up to 850 hPa, then increases
167 linearly with decreasing pressure to 2.3 m/s at 300 hPa, before decreasing to 1.8 m/s
168 at 50 hPa, and then rapidly increasing to 2.7 m/s higher up. For temperature, the
169 assumed observation error increases from 0.9 K at the surface to 0.6 K at 400 hPa,
170 then inflates to about 1.3 K at 50 hPa and then quickly further increases up to 1.6 K
171 higher up. After the production of ERA-PreSAT it was realized that these profiles had
172 inadvertently been swapped in some occasions. In the IFS data assimilation system,
173 PILOT data is expected as a function of height whereas TEMP data is expected as a
174 function of pressure. However, for the historical data, all combinations occur.
175 Unfortunately, PILOT data as a function of pressure was erroneously assigned
176 observation errors as a function of height, while a similar error was made for TEMP
177 data as a function of height.

178 Given the fact that the modern network is of (much) higher quality than the historical
179 data (see Wartenburger et al. 2013), the historical upper-air data are probably assigned
180 errors that are too small, and consequently given too much weight. Also, no bias
181 corrections were applied to the observations, except for the CHUAN 'c' records that
182 contain RAOBCORE v1.3 (Haimberger, 2007) bias adjustments. This absence of bias
183 correction is suboptimal, since large systematic errors are known to exist in the
184 observations. Known issues include for example a radiative warm bias for high
185 temperature profiles, particularly over the Former Soviet Union (Grant et al. 2009)
186 and systematic errors in wind direction for part of the early US pilot network
187 (Ramella-Pralungo and Haimberger 2014).

188 Clearly, the absence of dedicated background errors, the mixing of all observational
189 sources without any prior duplicate removal, the prescription of probably too small
190 observation errors (plus occasional mix-up in the vertical), and the neglect of
191 observation biases are duely acknowledged as non-optimal. However, these issues are
192 difficult to spot and resolve upon first trial. Owing to project time constraints it was
193 not feasible to correct these in a rerun of ERA-PreSAT within the limited time frame
194 of the ERA-CLIM project. Nevertheless, given the ERA-20C baseline without any

195   upper-air assimilation, the rest of this paper demonstrates that the addition of upper-

196   air data in ERA-PreSAT, albeit in a suboptimal framework, allows to assess the

197   enhancement of the reanalysis product, far outweighing the suboptimal usage of these

198   observations.

199   Figure 1 presents a time-line of the availability during the ERA-PreSAT period for the

200   four upper-air records and the assimilated. Although the largest dataset is represented

201   by UADB-2, it is seen that the recently digitized ERA-CLIM data improve

202   considerably the availability of temperature soundings before 1943. Regarding data

203   usage, there is quite some competition between the CHUAN-R and CHUAN-C sets

204   for the obvious reason that these sets are based on the same observations. It appears

205   that the screening in general favours the CHUAN-C dataset, which indicates that

206   corrected observations may generally be more consistent with the background than

207   uncorrected observations. Also, it is very reassuring that most of the ERA-CLIM data

208   is actually selected for assimilation, as it indicates most likely independent, new,

209   timeseries, and not inconsistent with other observations (either or both such condition

210   would have resulted in many data rejected).

211   The evolution of the global coverage is illustrated in Figure 2, which shows the

212   average daily number of actively used observations accumulated in 5x5 degree boxes

213   for the years 1943, 1950, 1957 and 1964. From this it emerges that initially

214   temperature records were very sparse and mainly concentrated over Northern Europe

215   and Russia (from 1939), South Korea and China (from 1942), Northern South

216   America and Northern Australia (from 1943). Data from India and Pakistan is

217   available between 1939 and 1941 (not shown). From 1946 onwards radiosonde data

218   over the United States of America (US) became available, the Russian network

219   expanded, while the West-European network expanded rapidly in 1948. From around

220   1957 more soundings became available from South America and South Africa. The

221   availability of wind profiles was already quite good over the US from 1939, Southern

222   Europe, India, Korea and East China. More sparse data was available from South

223   America and Central Africa. In 1943 there was a boost in wind soundings over the

224   Eastern part of the US, likely related to the 2nd World War. There was a further boost

225   over the entire US from 1948. From 1962 there has been a rapid increase in the

226   availability of both upper-air wind and temperature observations over the northern

227   hemisphere oceans.

228

3. Data used for comparison

3.1. 20CR and other Reanalysis data

ERA-20C and ERA-PreSAT are compared with Twentieth Century Reanalysis (20CR) version 2. 20CR which is a 3-dimensional, 6-hourly global atmospheric dataset and is based on the assimilation of surface and sea level pressure observations into the US National Centers for Environmental Prediction Global Forecast System atmosphere/land model (NCEP/GFS, Saha et al. 2010). It is run at a resolution of T62 in the horizontal and 28 hybrid sigma-pressure levels in the vertical (Compo et al. 2011). Monthly mean sea surface temperature and sea ice concentration from the HadISST dataset (Rayner et al. 2003) are used as boundary conditions. The assimilation was performed using a variant of the Ensemble Kalman Filter, and 56 ensemble members were used. In this study, however, we only address the ensemble mean.

For further comparisons we also used the reanalyses ERA-40 (Uppala et al. 2005), ERA-Interim (Dee et al. 2011) and JRA-55 (Kobayashi et al. 2015).

In addition, several comparisons are made to the ERA-20CM (Hersbach et al. 2015) model integration.

3.2. Statistical reconstructions

In addition to reanalysis data, we also compare ERA-PreSAT with monthly statistical reconstructions of global upper level fields. Three different reconstructions are used, termed BL (Brönnimann and Luterbacher 2004), REC1 (Griesser et al. 2010) and REC2 (Brönnimann et al. 2012a) hereafter.

All three reconstruction approaches are based on principal component (PC) regression. All of them use historical upper-air and surface data (sea-level pressure and station temperatures) as predictors and calibrate these data against reanalysis fields for the past few decades. BL focused on the 1939-1945 period and produced fields of temperature and geopotential height (GPH) at six levels (850, 700, 500, 300, 200, and 100 hPa) for the northern extra-tropics by calibrating against NCEP/NCAR reanalysis (Kistler et al. 2001). REC1 uses the same method and same output fields (but now global, *i.e.,* reconstructions were produced separately for the regions 15°-90° N, 20° S-20°N, and 90° S-15° S, and back to 1881), but large amounts of additional

261 upper air data. Moreover, it was calibrated against ERA-40. REC2 has the same

262 output levels but now also zonal and meridional wind components. It also uses PC

263 regression calibrated against ERA-40. However, REC2 is a grid-column-by-grid-

264 column reconstruction. For each grid column, only predictors from a cone of

265 influence around that grid column are considered. A minimum amount of upper-level

266 observations is required, and weights are attributed such that upper-air data contribute

267 at least 50%. Thus, unlike in BL or REC1, no stationarity of large-scale spatial

268 patterns is assumed. However, grid columns away from upper-air observations have

269 no data, and the resulting fields are not necessarily smooth or physically consistent.

270 REC2 is thus more akin to an interpolation of upper-level observation data.

271

272 **3.3. Total column ozone data**

273 Historical total column ozone data provide an interesting opportunity to independently

274 evaluate the performance of the historical reanalysis datasets. We use historical ozone

275 data from the World Ozone and Ultraviolet Radiation Data Center (WOUDC) from

276 1939 to 1963. Among the series are long series such as the well-studied series from

277 Arosa, Switzerland (46.8° N, 9.7° E; Staehelin et al. 1998) or Dobson's original series

278 from Oxford, UK (51.8° N, 1.2° W; Vogler et al. 2007), but also many shorter series

279 (see Brönnimann et al. 2003, for an overview). We use the same selection as in

280 Brönnimann and Compo (2012), but some of the stations used in that study do not

281 have data after 1939. Table 2 gives a list of the stations and number of daily values.

282

283 **4. Results**

284 **4.1 Forecast skill.**

285 As described above, the ERA-PreSAT reanalysis was set-up in exactly the same way

286 as ERA-20C. The only difference is the usage of upper-air data. This, therefore,

287 enables a very clean assessment of the impact of these data. For both ERA-20C and

288 ERA-PreSAT, a ten-day forecast had been integrated from each 00UTC analysis. This

289 allows for the assessment of the potential value of the upper-air data on forecast skill

290 in case they had been available in near-real time and the current data assimilation

291 scheme had been available at the time. Resulting forecast scores for the anomaly

292 correlation coefficient of the geopotential at 500 hPa height are presented in Figure 3.

293 It displays the average number of days for which the forecast had been excellent

294 (90%), good (80%) and on the edge of just being better than climatology (60%) over

295 the northern hemisphere (top) and Europe (lower panel). It shows an initial small or

296 neutral impact for the early 1940s but already in the 1950s there is a dramatic gain of

297 about 1.5 days. Especially the sudden large increase in forecast skill around 1948 over

298 Europe is noteworthy. It coincides with the large increase of wind soundings over the

299 US. A similar, though smaller pattern is seen for 1944. A synoptic example of this

300 improvement of forecast skill has been studied for the D-Day landing in June 1944

301 (Simmons et al., 2015). The skill of ERA-PreSAT outperforms the ERA-40 reanalysis

302 (Uppala et. al. 2005, dashed curves), which latter is better than ERA-20C. This

303 comparison should be handled with some care, since due to the difference in the

304 length of assimilation windows (as detailed in the caption of Figure 3), the ERA-40

305 forecasts could have been disseminated 18 hours before those for ERA-20C and ERA-

306 PreSAT.

307 The initial decline in scores over the northern hemisphere is thought to be the result of

308 the decrease in the availability of observations during the 2nd world war. It especially

309 applied to North America (not shown). Apparently the first upper-air soundings were

310 not able to reverse this picture. Over Europe, however, the positive impact emerged

311 right from the early 1940s, which, again, is likely the result of the availability of (on-

312 average upstream) wind profiles over the US. It is also interesting to note that for

313 Europe the best forecast scores are achieved around 1960 and that afterwards some

314 form of decline is apparent. Such decline is not visible over the North America and

315 East Asia (not shown).

316

317 **4.2. Basic energetic considerations**

318 To explore the evolution of the energetic state of the atmosphere in the different

319 ECMWF reanalyses, we consider vertically integrated total energy from the different

320 datasets averaged over different periods of time, choosing 2000-2009 as reference

321 period. We choose 1939-1944 and 1961-1966 representing the early and late periods

322 of ERA-PreSAT, respectively. In order to remove the impact of different model

323 topographies and differences in the mean circulation, i.e. regional mean surface

324 pressure values, we present a comparison of zonal mean vertically averaged total

325 energy from the respective datasets in Figure. 4a.

The early ERA-Interim period (1989-1999) shows only slightly lower values compared to the reference period (2000-2009), except for the Arctic, where strong warming was present during the 2000s. Atmospheric energy in ERA-PreSAT exhibits remarkable differences compared to ERA-Interim. During the early period (1939-1944), ERA-PreSAT shows a reasonable energetic state north of about 30N where upper-air observations were available already at that time. The increasing number of upper air observations all over the globe is reflected in a higher energetic state of ERA-PreSAT at all latitudes by 1961-1966. During that time, this reanalysis is already in very good agreement with the early ERA-Interim period (1989-1999). This indicates that the climatological state of the assimilating model without upper-air observations is energetically too low.

This impression is confirmed when examining ERA-20C and ERA-20CM which do not assimilate any upper-air observations. Although each of these datasets shows a relative increase of specific energy over time, consistent with global warming, both reanalyses exhibit values about 0.5% low when compared to ERA-Interim during the 2000-2009 period. As the by far largest amount of atmospheric energy is represented by enthalpy, we conclude that the assimilating model of ERA-20CM, ERA-20C, and ERA-PreSAT has a cold bias, translating to about 1K for 2000-2009.

The gradual evolution of the atmospheric state in ERA-PreSAT can also be seen from the zonal mean temperature structure (Figure 5). While during 1939-1944 tropospheric temperatures in ERA-PreSAT are higher than in ERA-20C mainly north of 30N (Figure 5a), positive differences are present globally during 1961-1966 (Figure 5b). As a reference panel c) shows ERA-Interim-ERA-20C differences in the period 1980-1989. The pattern looks quite similar to panel b) and shows the cold bias in ERA-20C. It indicates that the state of ERA-PreSAT in the 1960s was already quite realistic, except perhaps in the Southern Ocean and Antarctica when there were still too few observations. Figure 5 also shows that differences are comparatively small in the lower troposphere, indicating that differences in SSTs can be ruled out as a cause for the found differences (see also Figure 4b). Moreover, Figures 5b and 5c imply that the modelled troposphere is statically too unstable when no upper-air observations are assimilated. The hemispheric asymmetry of observations going into ERA-PreSAT in the early period obviously affects analysed stratospheric temperatures, with too cold (warm) temperatures above about 300hPa in the Southern (Northern) Hemisphere when compared to ERA-20C (Figure 5a). The stratospheric temperature differences

360   also explain the very low specific total energy of ERA-PreSAT south of about 45S

361   during 1939-1944 (see Figure 4a). Since the differences in stratospheric temperatures

362   are not present for the later period (Figure 5b), we speculate that the hemispherically

363   asymmetric atmospheric state in ERA-PreSAT during the early period adversely

364   affects stratospheric circulation, which leads to the described spurious temperature

365   patterns.

366   Besides the temporal evolution of the number of upper-air observations, their spatial

367   distribution is important too. An uneven distribution of observations can set up

368   unrealistic gradients of atmospheric energy, which likely affects atmospheric energy

369   transports. Cross-equatorial energy transports as presented in Figure 6 are a quite

370   sensitive diagnostic in this respect. ERA-20CM exhibits quite stable negative values

371   around -0.17 PW, in good agreement with ERA-Interim (~ -0.25 PW; compare also

372   Mayer and Haimberger 2012). Transports from ERA-20C in the 1940s are too weak

373   but approach ERA-20CM values later in the period. Transports from ERA-PreSAT

374   have the wrong sign in the 1940s, but approach ERA-Interim values in the 1960s.

375   This behavior is likely caused by the unrealistic interhemispheric temperature

376   gradients in the 1940s seen in Figure 5 which gradually disappear in the 1960s. The

377   reason for the changing temperature gradients is mostly the changing coverage of

378   upper air data. Surface wind and pressure observations probably also contribute to the

379   unstable cross-equatorial energy transport in ERA-PreSAT, as ERA-20C shows

380   similar variations.

381

382   **4.3. Comparison with independent observations and reconstructions**

383   **4.3.1. Comparison with ERA-CLIM upper-air data**

384   Apart from the NCEP/NCAR 50-Year Reanalysis (Kistler et al. 2001) and a few very

385   short term reanalyses, ERA-PreSAT is the only reanalysis dataset where upper air

386   data before 1958 have been assimilated. Despite some technical issues noted above, it

387   turned out that the early data are generally of high quality and have a profound

388   influence on the atmospheric state.

389   Figure 7 shows that departures between radiosonde observations and ERA-PreSAT 12

390   hour forecasts (referred to as obs-bg) for a given site over the US are much smaller

391   (0.52K standard deviation at the 200hPa level) than departures between observations

392   and ERA-20C analyses (obs-an 1.21K at this level).Note that for ERA-preSAT obs-bg

393 departures have been chosen since the background forecasts at a given radiosonde site

394 are largely independent of the respective radiosonde observations (which is not true

395 for the ERA-preSAT obs-an since the radiosonde data have been assimilated). For

396 ERA-20C the analysis data are completely independent of radiosonde observations

397 and therefore obs-an departures can be used. It is also noteworthy that the mean of

398 the departures is much smaller for ERA-preSAT, whereas ERA-20C seems to have a

399 cold bias compared to the radiosonde observations.

400 The small obs-bg departures highlight the overall good quality of the early radiosonde

401 data and also indicate a good short term predictive skill of the ERA-PreSAT

402 assimilating model. The small departures enable much more efficient detection of

403 potential breakpoints in the radiosonde observation records than the ERA20C

404 departures. In this particular case the change from BENDIX-FRIES to VIZ

405 radiosondes 1957 has caused a shift of one degree that is barely detectable from the

406 from ERA-20C obs-an departures using a popular homogeneity (SNHT,

407 Alexandersson, 1986; Haimberger 2007) but is very well detectable from ERA-

408 PreSAT obs-bg departures. The shift in 1948 also coincides with metadata for this

409 station according to the CARDS data set (Eskridge et al. 1995).

410 Since the difference series between ERA-PreSAT 12h forecasts and ERA-20C (not

411 shown) indicates no breaks in 1948, 1950 and 1957 the detected breaks are likely

412 caused by changes in the radiosonde records. This and many further examples indicate

413 the high potential of these reanalysis departure time series for automatic data quality

414 control and homogenization of early aerological observations

415

416 **4.3.2. Comparison with daily total column ozone anomalies**

417 In order to address the reliability of day-to-day variability in ERA-PreSAT and other

418 reanalyses (ERA-20C, 20CRv2), we compared total column ozone to observations.

419 For this purpose we subsampled the reanalyses to the observations (both in time and

420 space) and removed for each station the annual cycle by least-squares fitting and

421 subtracting the first two harmonics of the day of year. Maps of the correlations are

422 shown in Figure 8. The general structure shows highest correlations over the northern

423 mid-latitudes (a feature known since the 1920s; Dobson and Harrison 1926), where

424 column ozone and atmospheric dynamics are intrinsically linked (Vaughan and Price,

425 199, Orsolini et al. 1998; Barriopedro et al. 2010). Correlations drop towards the

426 Arctic and particularly rapidly towards the monsoon regions and the tropics, where

427 day-to-day variability of total column ozone is smaller and less strongly linked to the

428 circulation near the tropopause and hence is more difficult to capture in a reanalysis

429 (Compo et al. 2011). This behaviour is known from previous studies.

430 The anomaly correlations are generally high (note that also the historical observations

431 from 1939-1963 are far from perfect). Our previous work has shown surprisingly high

432 correlations between 20CR and historical total column ozone data (Brönnimann and

433 Compo, 2012). Here we find even higher correlations with the new ERA reanalysis

434 datasets. ERA-20C shows slightly (but consistently) higher correlations than 20CRv2.

435 Interestingly, correlations are generally highest for ERA-PreSAT, where values up to

436 0.8 are found over northern Europe. The improvement over the Arctic and over the

437 Indian monsoon region also is particularly noteworthy. This analysis shows that

438 assimilating upper-air data considerably improves the atmospheric fields at higher

439 levels.

440

441 **4.3.3. Comparison of month-to-month variability in upper-air data**

442 In a next step we analysed month-to-month variability. For this analysis we used

443 monthly upper-air data from the USA, where a relatively dense radiosonde network

444 was operating since 1939, but most series are only available as monthly means until

445 1945 and hence were not assimilated (Brönnimann 2003). We again subsampled the

446 reanalyses as well as the reconstructions to the station locations and subtracted the

447 mean annual cycle based on the 1939-1944 period. The number of available months

448 was between 48 and 66, which is sufficient for statistical analyses. Table 3 shows the

449 anomaly correlations for four selected stations covering tropical latitudes to

450 midlatitudes); similar results were found for other locations. Note that these monthly

451 data were used in all three reconstructions, hence they are not independent.

452 ERA-PreSAT shows generally higher correlations for geopotential height and for the

453 700 hPa level than the other renalayses. At midlatitudes (Sault St. Marie, 46.5° N,

454 Washington DC, 38.9° N) it has the highest correlations of all reanalyses. In the

455 tropics (Islas Santanilla, 17.5° N) all reanalyses become much worse except at the

456 lowest level. Also one of the reconstructions (REC1) becomes worse while the other

457 two (BL2004, REC2) still yield high anomaly correlations that even increase with

458 altitude. Among the reanalyses, ERA-20C performs better than the others. Results for

14

459   the subtropical location (Miami, 25.8° N) are in between those from the midlatitudes
460   and for the tropics.

461

462   **4.3.4. Interannual variability**

463   For the analysis of interannual variability, we focused on Arctic temperature, which
464   showed peculiar changes between the 1930s (the early twentieth century Arctic
465   warming) and the 1960s (a cold period in the Arctic). We presented a systematic
466   assessment of reanalyses and reconstructions with respect to Arctic temperature
467   profiles in a previous paper (Brönnimann et al. 2012b) and here would like to report
468   on ERA-PreSAT in this respect (see also Wegmann et al. 2016).

469   The focus is on 700 hPa temperature in winter (Dec.-Feb.), which is the season and
470   level where we expect atmospheric circulation changes to have an impact on Arctic-
471   wide temperatures. Table 4 show correlations between different datasets (note that
472   here we have only one reconstruction, REC1, as REC2 does not completely cover the
473   Arctic and BL2004 ends in 1947, thus leaving too few degrees of freedom) for the
474   winters 1939/40 to 1966/67. For this comparison REC1 was extended from 1957 to
475   1967 using ERA-40.

476   Although none of the datasets stands out, Table 4 shows that ERA-PreSAT improves
477   over ERA-20C as it shows higher correlations with the other two datasets. ERA-
478   PreSAT and 20CRv2 are similar in that respect. Note that 20CRv2 has an error in the
479   specification of sea ice, which might affect the results. The error is fixed in the latest
480   version v2c, which is not yet published and therefore not systematically analysed here
481   (correlations are very slightly higher).

482   Anomalous climatic conditions prevailed in the northern extratropics in the late
483   winters of 1940-1942. Arguably initiated by El Niño conditions in the tropical Pacific,
484   the midlatitude upper troposphere and stratosphere exhibited a strong climatic
485   signature expressing a weakened polar vortex and warm lower stratosphere over
486   northern Siberia (Brönnimann et al. 2004). At the surface, cold winter dominated over
487   northeastern Europa (even affecting the Second World War) while winters were warm
488   in Alaska. Contrasted against the neighbouring winters of 1939, 1943 and 1944, the
489   average of the 1940-1942 winters is among the strongest signals in the climate system
490   on multiannual time scales. The anomaly is partly reproduced from sea-surface

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491 temperatures alone. It is therefore an easy starting point for comparing the different
492 data products. We expect strong anomalies in the upper troposphere and stratosphere.

493 In fact, the difference between January-April averages of 1940-1942 minus 1939,
494 1943, and 1944 (Figure 9) reveals a characteristic structure in the upper troposphere
495 and lower stratosphere that appear in a very similar manner in all datasets.
496 Interestingly, except for the model simulations (ERA-20CM), all datasets show even a
497 stronger signal than REC2004, on which our original publication was based
498 (Brönnimann et al. 2004). All reanalysis datasets show a pronounced warming of the
499 polar stratosphere akin of sudden stratospheric warming events (SSWs). More
500 frequent SSWs were suspected from observations, which however are too scant and
501 the suspected dates of SSWs do not fit well with those in ERA-PreSAT (not shown).
502 ERA-PreSAT shows a somewhat stronger warming and polar vortex response than
503 ERA-20C and 20CRv2, respectively. Overall, all datasets pass this first test and at the
504 same time further corroborate the abnormality of climate during the period 1940-
505 1942.

506

507 **4.4. The Quasi Biennial Oscillation**

508 The representation of the Quasi Biennial Oscillation is a useful benchmark for
509 reanalysis datasets. In full reanalysis it is well represented but it poses a tough
510 challenge for surface data only reanalyses as well as climate models since it is
511 maintained by complicated wave interaction mechanisms (Baldwin et al. 2001).

512 ERA-PreSAT is almost a surface data only reanalysis in the early 1940s, particularly
513 in the Tropics, with the amount of upper air data gradually increasing also in the
514 tropics in the late 1940s and early 1950s. As such one can observe the transition of the
515 QBO state from a purely modelled one to a state well constrained by upper air data.

516 While there are many measures to quantify the QBO, we use here the zonally
517 averaged zonal wind at the 50 hPa level averaged between 20N and 20S as a proxy.
518 This quantity can be reliably estimated from reanalyses as well as from relatively
519 sparsely distributed radiosonde stations. Figure 10 indicates that ERA-PreSAT has a
520 reliable QBO pattern back to the early 1950s, which is a significant advance
521 compared to what was available before from reanalyses but still leaves room for
522 improvement since statistical reconstructions of the QBO are available back to the
523 early 1900s (Brönnimann et al. 2007). In the 1940s, while there is still some upper air

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524 data, ERA-PreSAT has difficulty to reproduce the QBO amplitude as do the surface

525 data only reanalyses. The inclusion of newly digitized data from Meteo-France as well

526 as better representation of the QBO in future versions of the assimilating model may

527 help to extend the period of realistic QBO representation in reanalyses back even

528 further.

529

530 **4.5. Tropical cyclones**

531 One of the main applications of historical reanalyses is the analysis of past weather

532 extremes, either in order to improve statistics, for analysing decadal variability in

533 extremes, or in search of analogues for a present-day extreme. One example for the

534 latter could be Typhoon "Cobra", which struck the United States Pacific Fleet about

535 480 kilometres east of the Philippine island Luzon on 18 December 1944, inmidst of

536 World War II, killing about 790 people. This case is an interesting historical precedent

537 for typhoon Haiyan in 2013 and therefore taken as an example. We compare the three

538 reanalyses with a historical weather chart from NOAA (see also Feuchter et al. 2014).

539 In Figure 11 we show the fields for 18 Dec. 1944, 6 UTC. All reanalyses show at least

540 a slight depression east of the Philippines. However, a tropical cyclone is only seen in

541 20CRv2, and also here the core pressure is much higher than indicated on the synoptic

542 chart. As mentioned in Poli et al. (2016), the ECMWF variational quality control

543 scheme of the observations has led to inadvertent exclusion or downweighting of

544 many best-track reports or other tropical cyclone data (see also Poli et al. 2015).).

545 This is also the case for "Cobra", where the tropical cyclone reports are also excluded

546 by the background check. This affects the representation of "Cobra" both in ERA-20C

547 and ERA-PreSAT. Hence, although a low pressure value of 988 hPa is presented to all

548 assimilation systems near the typhoon, values drop only to 1004.6 hPa and 1005.1 hPa

549 in ERA-20C and ERA-PreSAT, recpectively, but to 999.6 hPa in 20CRv2. Even

550 though during this period, upper-air data from neighbouring islands were assimilated

551 into ERA-PreSAT, the assimilation is not improved near the storm. More detailed

552 analyses of additional tropical cyclones will be presented in a forthcoming paper.

553 **5. Conclusion**

554 In this paper it is concluded that early upper-air data has great potential in improving

555 our knowledge on the troposphere and lower stratosphere in future climate reanalysis.

556 This was demonstrated by the production of a ERA-20C type reanalysis that covers

the period 1939-1967 and in addition to surface information had assimilated upper-air temperature and wind from three historical datasets. The analyses of this experimental reanalysis, ERA-PreSAT, and comparison with existing products and with independent upper-air observations, total column ozone, and other meteorological variables show the following:

- Biases in the northern hemisphere are largely reduced compared to surface data only reanalyses.

- The strong concentration of early upper air data to the northern extratropics in the 1940s created a strong interhemispheric asymmetry which is likely not realistic. This issue can presumably addressed by reducing the overall cold bias of the assimilating model and by correcting the generally warm biases of the assimilated early radiosonde data.

- The forecast skill in the northern hemisphere has increased substantially compared to surface data only reanalyses.

- Day-to-day and (in the northern extratropics) month-to-month correlation with independent data (total column ozone, upper-air data) increases.

- Interannual signals in the northern sub- and extratropics are well captured in all products.

- ERA-PreSAT display a signature of the stratospheric Quasi-Biennial Oscillation back to the 1940s.

- Like ERA-20C, tropical cyclones are not well represented in ERA-PreSAT.

ERA-PreSAT is an experimental product and will not be made available via a public data portal. Its prime purpose was to explore the usage and impact of early upper air data in climate reanalysis. Some short-cuts and errors had been made regarding the data ingestion. Examples are the non-optimal weight assigned to the observations, and the occasional mix up of such weights in the vertical. Despite such sub-optimal choices, the results of this experimental reanalysis are found to be very promising.

Overall ERA-PreSAT has shown that assimilating early upper air data substantially reduces uncertainties in the northern hemispheric atmospheric state back to the late 1930s. The inclusion of upper air data particularly from the tropics (Stickler et al. 2014) that have not yet been assimilated, together with measures to deal with the

588 strong N-S data density asymmetry can further improve results on the global scale, so
589 that future full reanalysis efforts can be sensibly extended further backward.

590 Upper-air data are available back to the late 1910s in substantial number on a large
591 (though not global) scale. Assimilating these observations will bring substantial
592 benefit to atmospheric reanalyses. In addition, the positive results as described in this
593 paper underline the importance of the recovery and digitization of historical data
594 records and the impact they will have on our knowledge on the state of the
595 atmosphere in the first part of the 20th century.

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Table 1. List of the historical upper-air data sets input to ERA-PreSAT. The observables Temperature (T), wind speed (Ws), wind direction (Wd), specific humidity (Q), relative humidity (R), dew-point depression $(T-T_d)$ and vertical coordinates pressure (P) and height (Z) are not available for all stations nor the entire period, especially for humidity and dew-point depression.

Dataset	Location	Available Period	Available Observables
NCAR UADB-2	http://rda.ucar.edu/datasets/ds370.1	Feb 1919 – Aug 2012	Z, P, T, Ws, Wd, RH
CHUAN v1.7 'Raw'	http://rda.ucar.edu/datasets/ds370.1	Jan 1904 – Mar 2007	Z, P, T, Ws, Wd, Q
CHUAN v1.7 'Corrected'	http://rda.ucar.edu/datasets/ds370.1	Jan 1904 – Mar 2007	Z, P, T, Ws, Wd
ERA-CLIM v0.9	University Bern	Oct 1899 – Dec 1972	Z, P, T, Ws, Wd, Q, RH, $T-T_d$

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Table 2. Historical total ozone stations used in this study (see Brönnimann et al. 2003). n denotes the number of days with observations within the period 1924-1963.

Station	Period	lon (° E)	lat (° N)	n
Aarhus	1952-1963	10.6	56.3	3462
Aldergrove	1952-1957	-6.2	54.7	1415
Arosa	1939-1963	9.7	46.8	6438
Camborne	1952-1953	-5.3	50.2	3283
College	1952-1957	-147.5	64.7	394
Dombas	1940-1946	9.1	62.1	1410
Edmonton	1950-1952	-113.5	53.6	557
Flagstaff	1954-1957	-111.7	35.2	463
Gulmarg	1955-1956	74.4	34.1	298
Hemsby	1952-1955	1.7	52.7	855
Lerwick	1939-1963	-1.2	60.1	3290
Magny	1955-1959	2.1	48.7	1054
Mount Abu	1951-1960	72.7	24.6	2278
New Delhi	1955-1957	77.2	28.6	920
New York	1941-1944	-73.9	40.9	899
Oxford	1939-1963	-1.2	51.8	6020
Rome	1954-1963	12.2	42.1	3152
Spitsbergen	1950-1962	15	78	1676
Srinagar	1956-1957	74.8	34.1	182
Tateno	1955-1957	140.1	36.1	409
Uppsala	1952-1963	17.6	59.9	2472

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725 **Table 3.** Month-to-month Pearson correlations (x100) with upper-air data at four locations in North

726 America, spanning latitudes between 17.5° N and 46.5 ° N, of three reconstructions (top three rows)

727 and three reanalyses (bottom three rows) for the 1939-1944 period. Correlations are given for

728 temperature (T) and geopotential height (Z) at the three levels 700, 500, and 300 hPa. Monthly

729 anomalies were expressed as deviations from the mean annual cycle over the 1939-1944 period,

	Sault St. Marie, 46.5°N, n=66		Washington DC, 38.9°N, n=66		Miami, 25.8°N, n=62		Islas Santanilla, 17.5°N, n=48	
	Z300/500/700	T300/500/700	Z300/500/700	T300/500/700	Z300/500/700	T300/500/700	Z300/500/700	T300/500/700
BL2004	83/89/86	83/89/88	96/95/95	91/93/94	92/93/94	67/86/91	77/71/40	74/63/22
REC1	82/86/79	77/88/88	93/92/91	82/89/89	83/88/89	53/82/74	26/26/33	43/35/47
REC2	89/93/93	77/93/93	96/96/96	80/91/93	91/91/92	84/87/86	76/64/57	80/72/72
ERA-PreSAT	84/91/93	71/80/89	87/91/93	62/79/90	60/80/91	37/55/61	-06/-07/36	08/06/39
ERA-20C	73/82/87	53/71/79	87/88/90	74/78/84	73/81/80	33/63/61	29/24/48	28/24/45
20CRv2	80/86/89	70/83/85	84/90/92	57/75/85	68/80/83	46/60/54	-01/09/39	-13/05/27

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731 **Table 4.** Pearson correlations of Dec.-Feb. mean temperature at 700 hPa north of 60° N from 1940 to

732 1961 in different data sets (see Wegmann et al. 2016)

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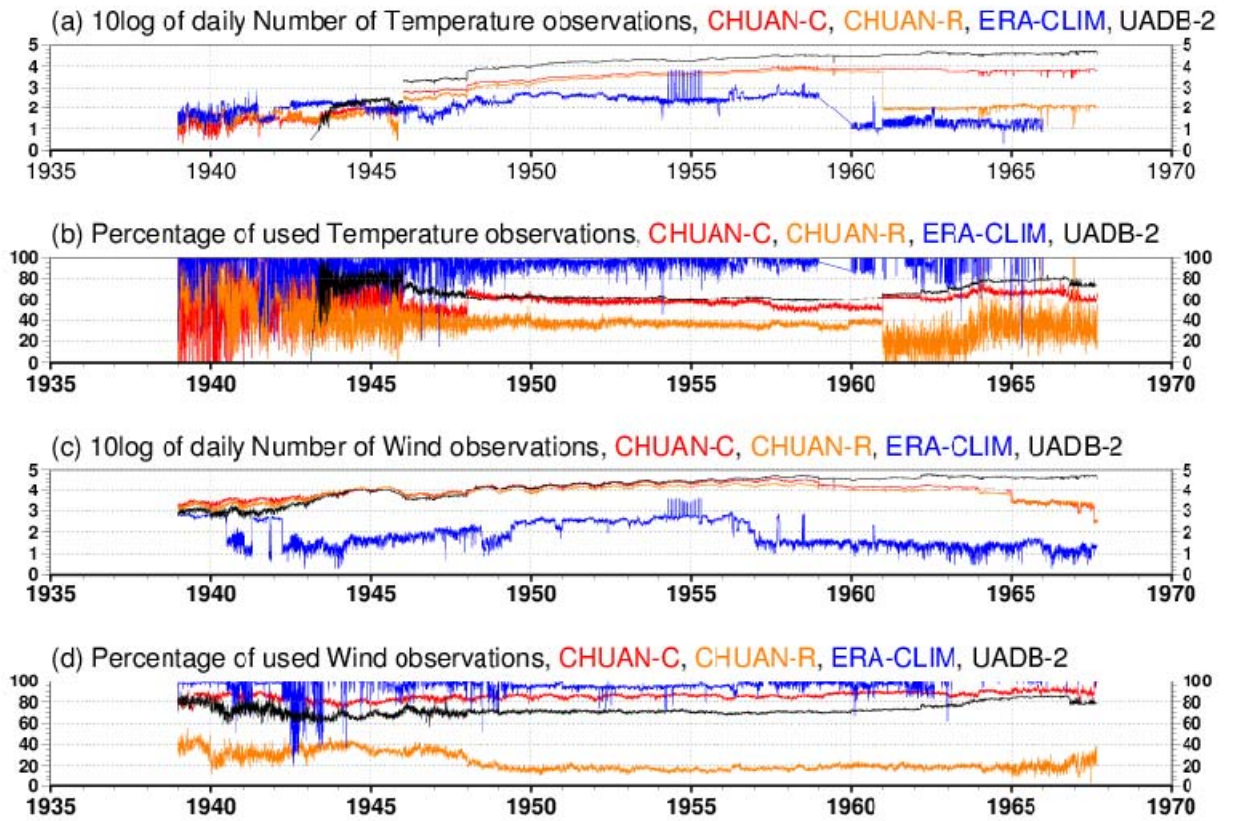|	20CRv2	ERA-20C	ERA-PreSAT	REC1
20CRv2	1	0.77	0.96	0.88
ERA-20C	0.77	1	0.80	0.68
ERA-PreSAT	0.96	0.80	1	0.87
REC1	0.88	0.68	0.87	1

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736 **Figures**

737

Fig.1: Time series of availability and usage of upper-air data in ERA-PreSAT for the
CHUAN v1.7 'corrected' (red)), CHUAN v1.7 'raw' (orange), ERA-CLIM v0.9
(blue) and UADB-2 (black) data sets.

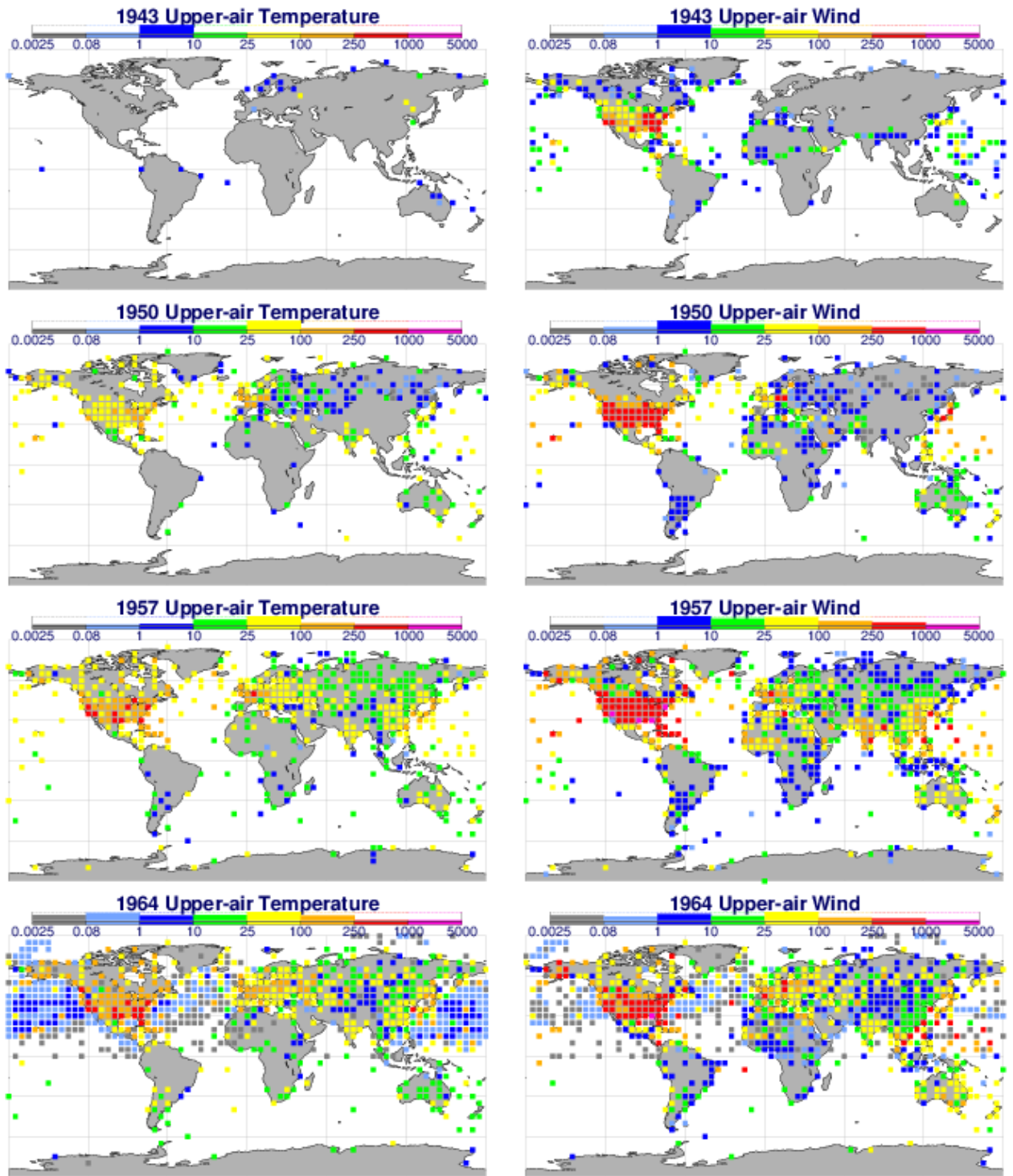738

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Fig. 2: Geographical distribution and number of observations actively assimilated in
ERA-PreSAT per day in 5x5 degree grid boxes, averaged over (from top to bottom)
1943, 1950, 1957 and 1964, for upper-air temperature (left) and wind (right). The
lowest two contour bounds of 0.0025 and 0.08 represent one observation in one entire
year and one observation per month, respectively.

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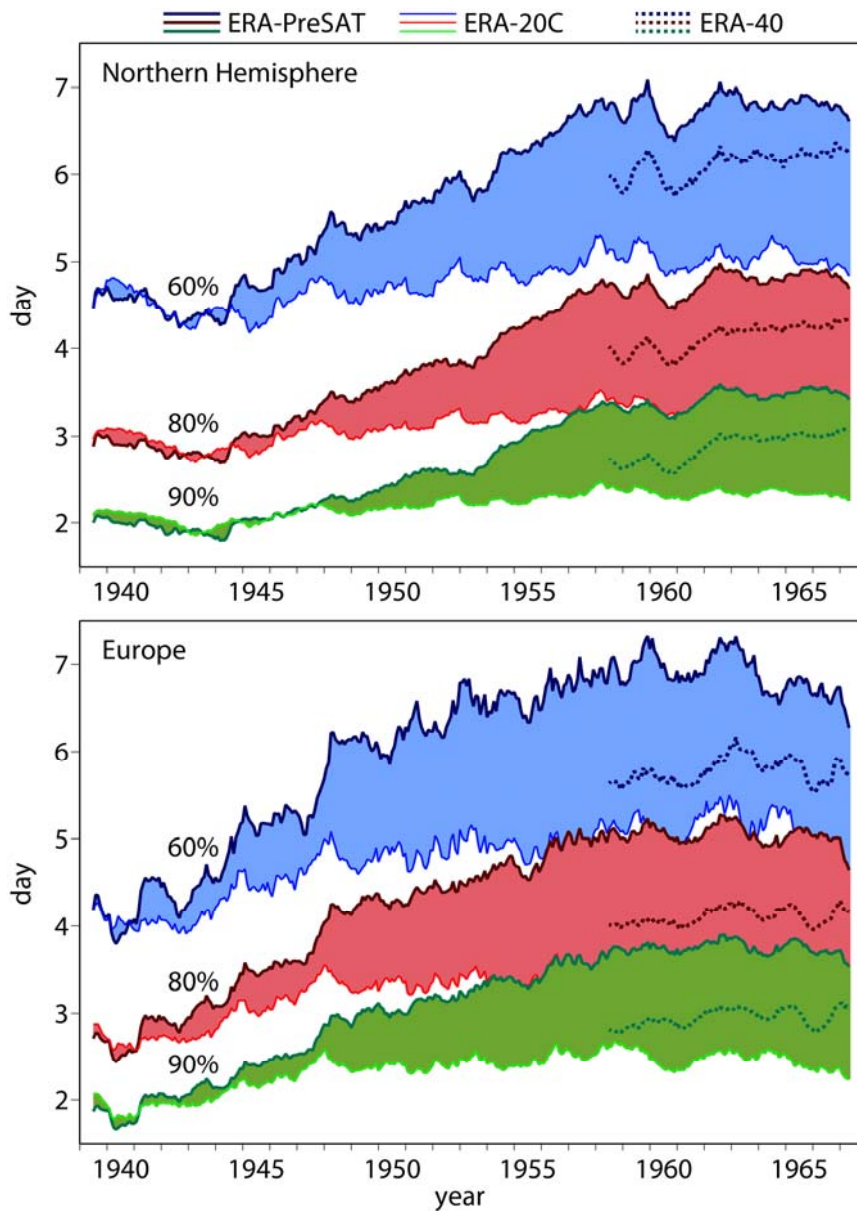
Fig. 3: Twelve-month running mean of the number of forecast days for which the northern hemispheric (top panel) and European (lower panel) anomaly correlation coefficient (geopotential at 500 hPa height) with respect to the own verifying analysis reaches 90% (green), 80% (red) and 60% (blue) for ERA-PreSAT (dark solid curves), ERA-20C (light solid curves) and ERA-40 (dotted curves). All forecasts started from 3 hours into the assimilation window, which means forecasts for ERA-20C and ERA-PreSAT (24-hour assimilation window) have benefitted from observations that were 21 hours into the future while only 3 hours in ERA-40 (6-hour window).

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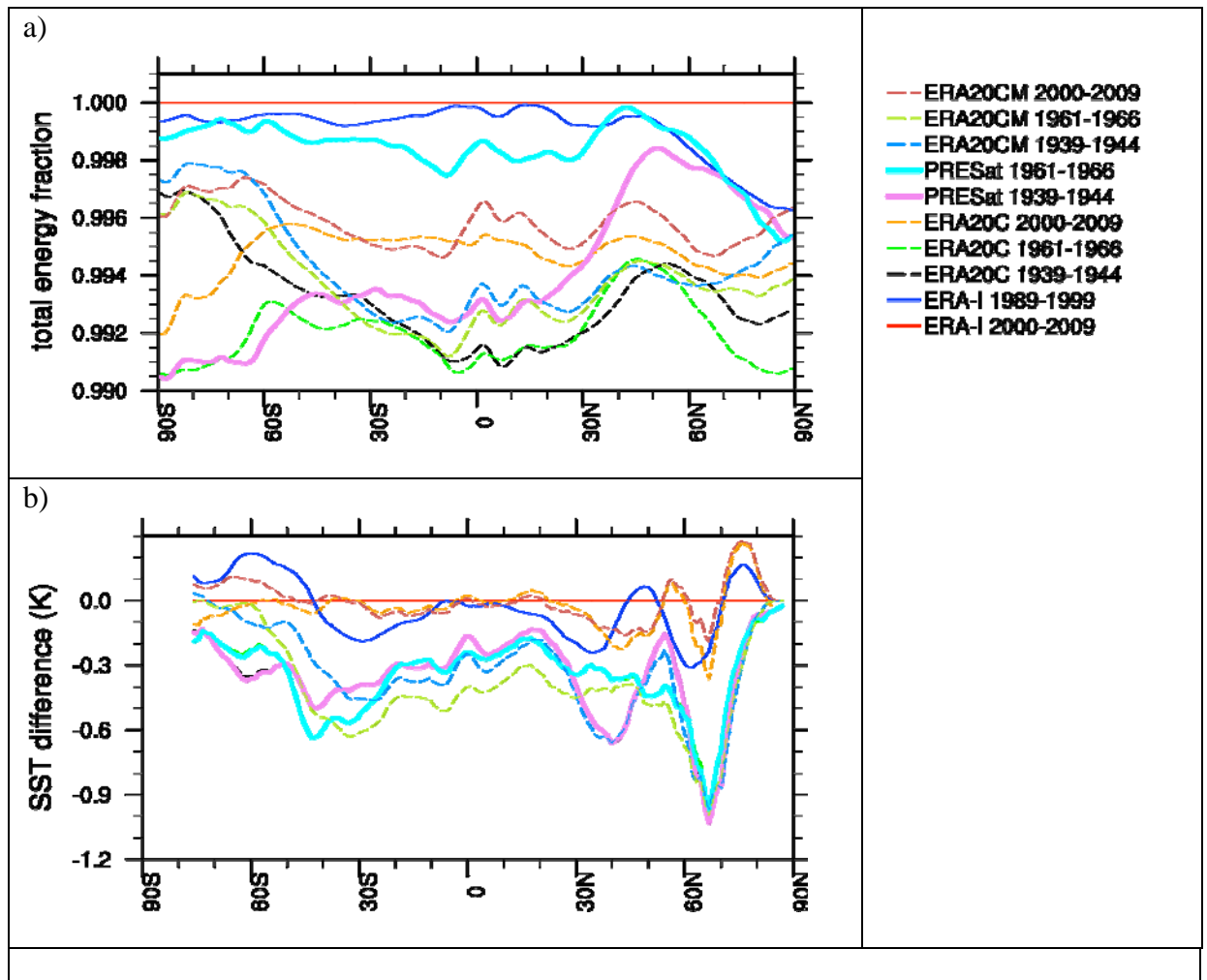
Fig. 4 a) Fraction of zonal mean specific total energy from
ERA20CM/ERA20C/ERA-PreSAT/ERA-I (ERA-Interim 1989-1999) and ERA-I for
the reference period (2000-2009); b) Difference of zonal mean SSTs from ERA-I
(2000-2009) and ERA20CM/ERA20C/ERA-PreSAT/ERA-I (1989-1999); The
different averaging periods are given in the legend.

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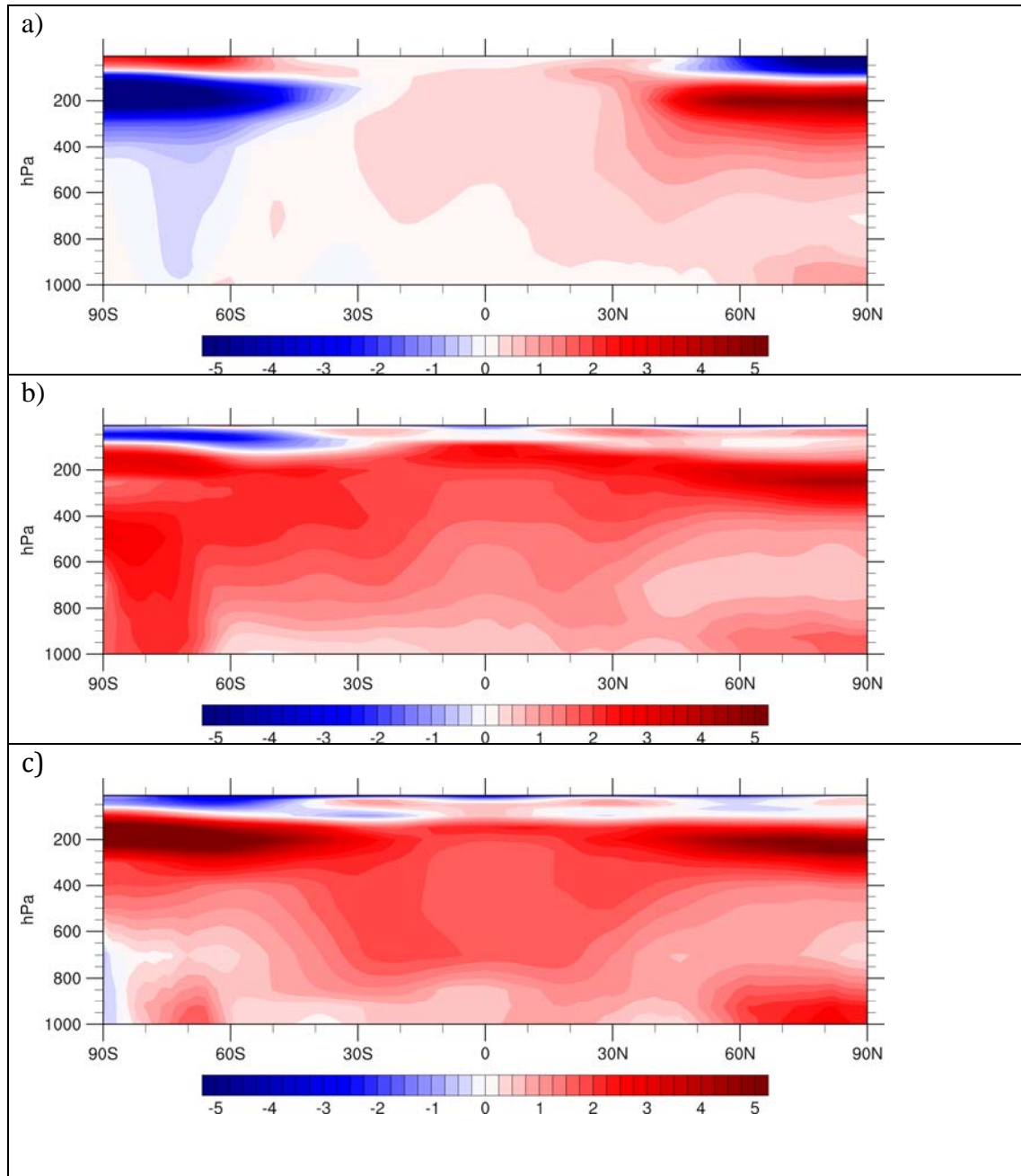
769   **Fig. 5** Difference of ERA-PreSAT and ERA-20C zonal mean temperatures for a)

770   1939-1944 and b) 1961-1966, and c) differences ERA-Interim-ERA-20C 1980-1989,

771   Units are K.

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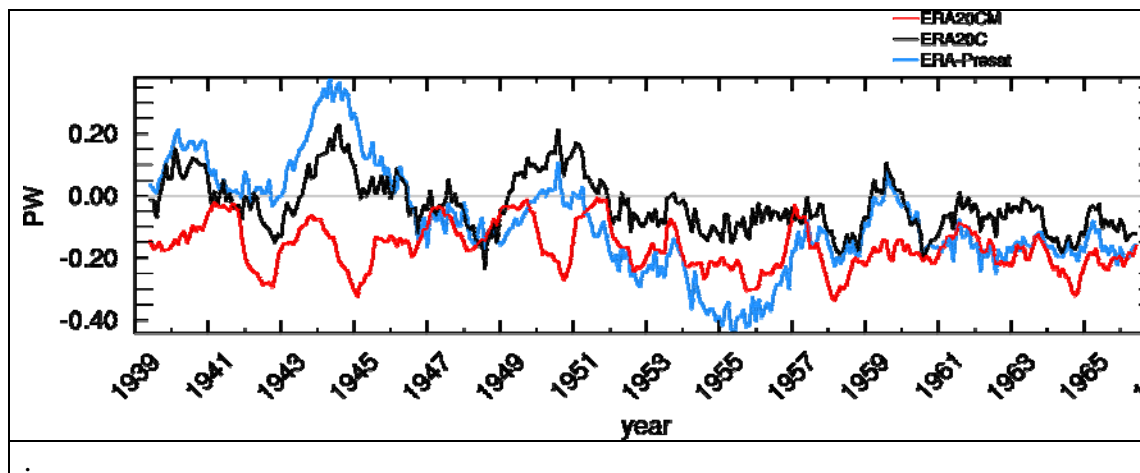
Fig 6. 12-month running mean total energy transport across the equator (positive northward) from ERA20CM, ERA20C, and ERA-Presat. The ERA-I reference value is -0.25PW.
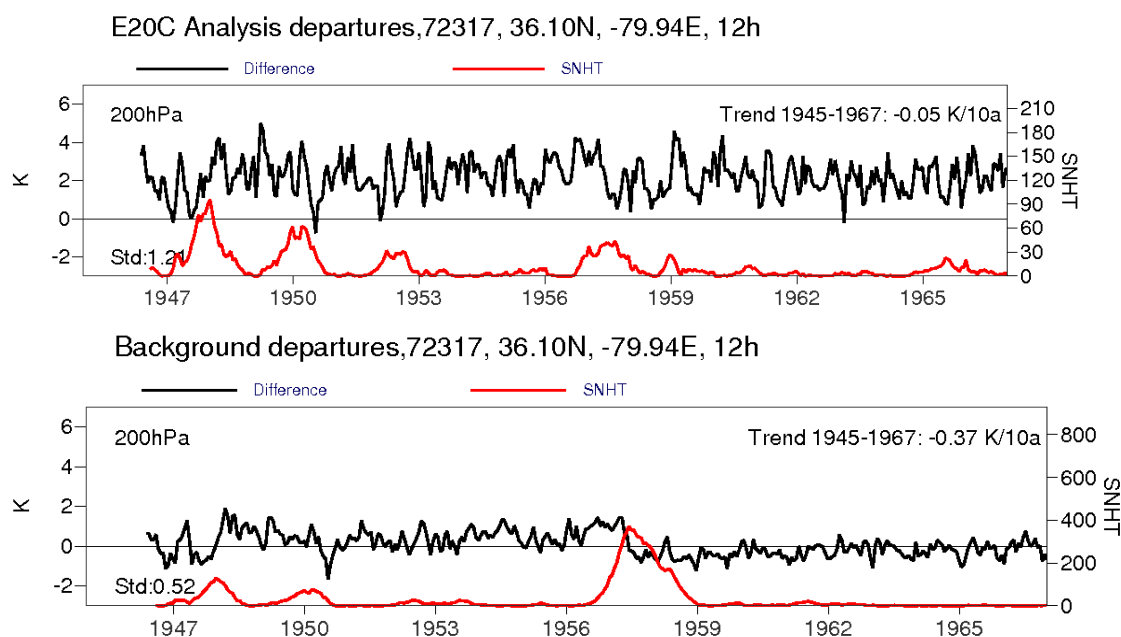
E20C Analysis departures,72317, 36.10N, -79.94E, 12h

Background departures,72317, 36.10N, -79.94E, 12h

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780   **Fig. 7***:* Time series of obs-ERA-20C analysis departures (upper panel, standard
781   deviation 1.21K) and obs-ERA-preSAT background departures (lower panel, standard
782   deviation 0.52K) for station Greensboro in the eastern US. Red curve (right axis) is
783   Standard Normal Homogeneity Test statistic as described in Haimberger (2007).
784   Sharp maxima with values above 50 indicate likely breakpoints. Note good temporal
785   correspondence of maxima in both panels, detection efficiency is better in lower panel
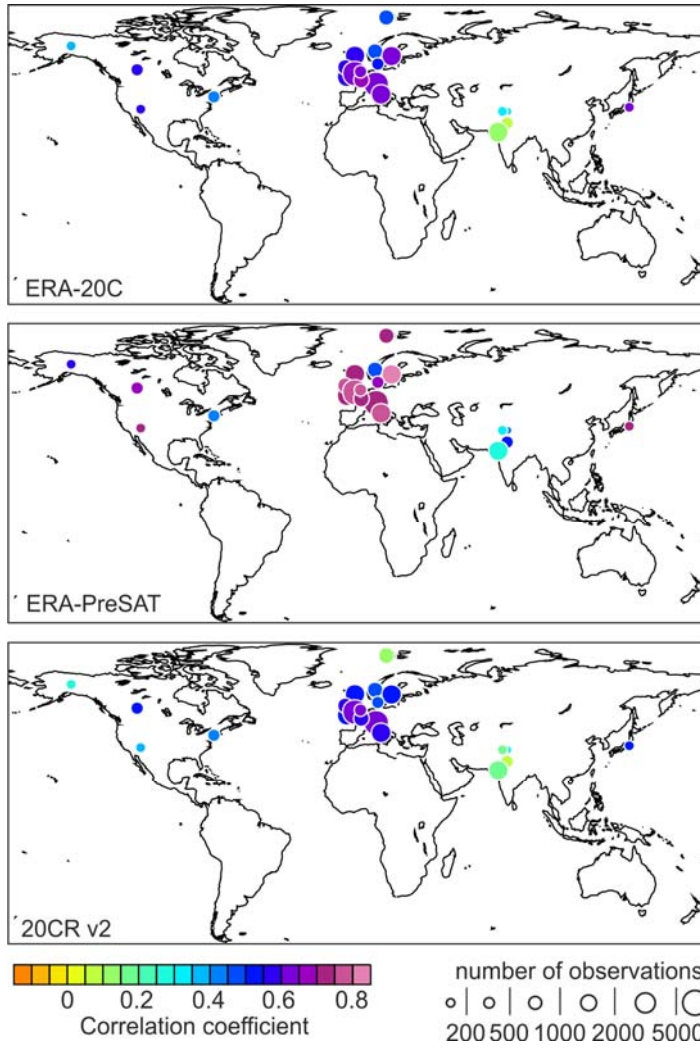786   due to smaller noise level.
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Fig. 8: Correlations between total ozone anomalies from reanalysis data sets and observations, 1939-1963. The size of the circle indicates the number of observations for the stations listed in Table 1 (see Brönnimann and Compo, 2012 for correlations with 300 hPa geopotential height).
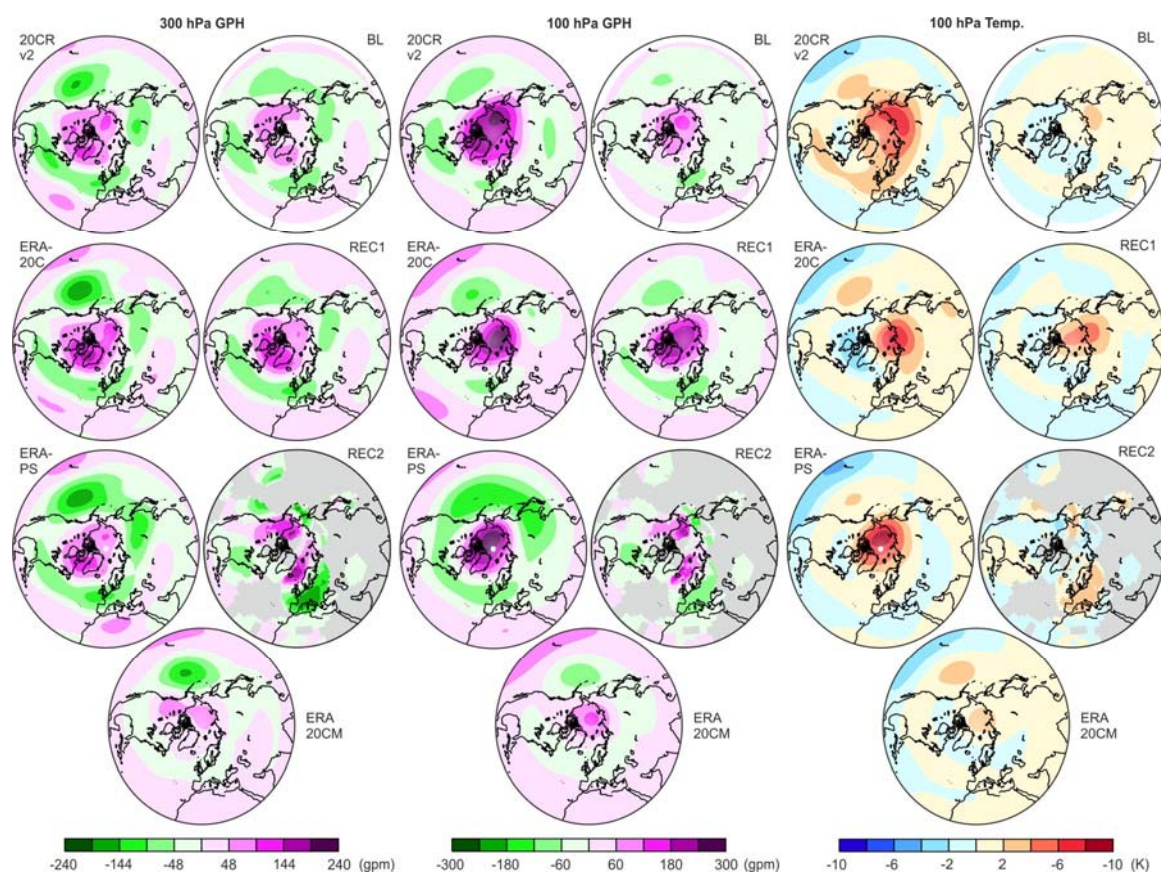
Fig. 9: Difference in (left) 300 hPa GPH, (middle) 100 hPa GPH and (right) 100 hPa temperature over the northern extratropics between the January to April period of 1940-1942 and that of the neighbouring years (1939, 1943 1944) from different data sets.
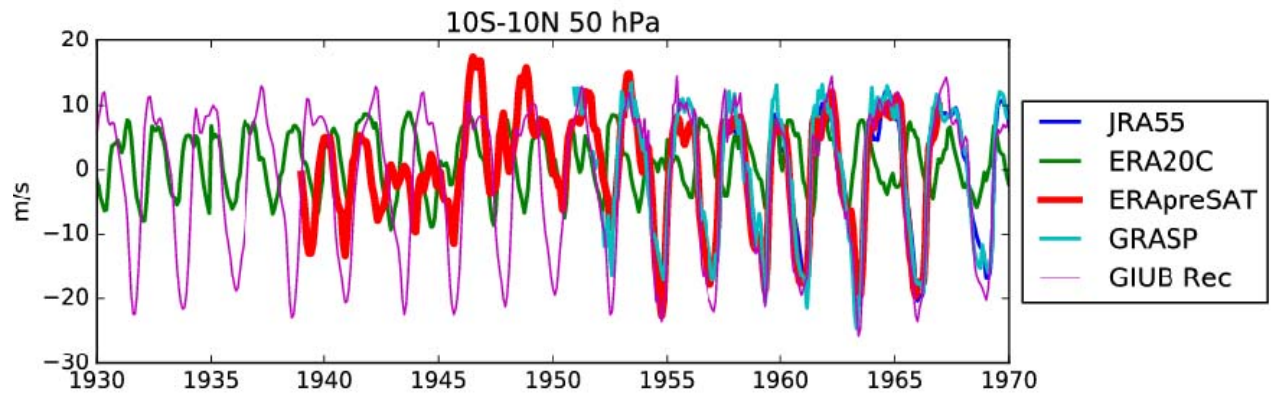
Figure 10: Time series of 50hPa u-wind component averaged zonally and over the
tropical belt for different reanalyses, one wind observation data set (GRASP) and the
reconstruction of Brönnimann et al. 2007 (GIUB Rec). Note that ERA-PreSAT is the
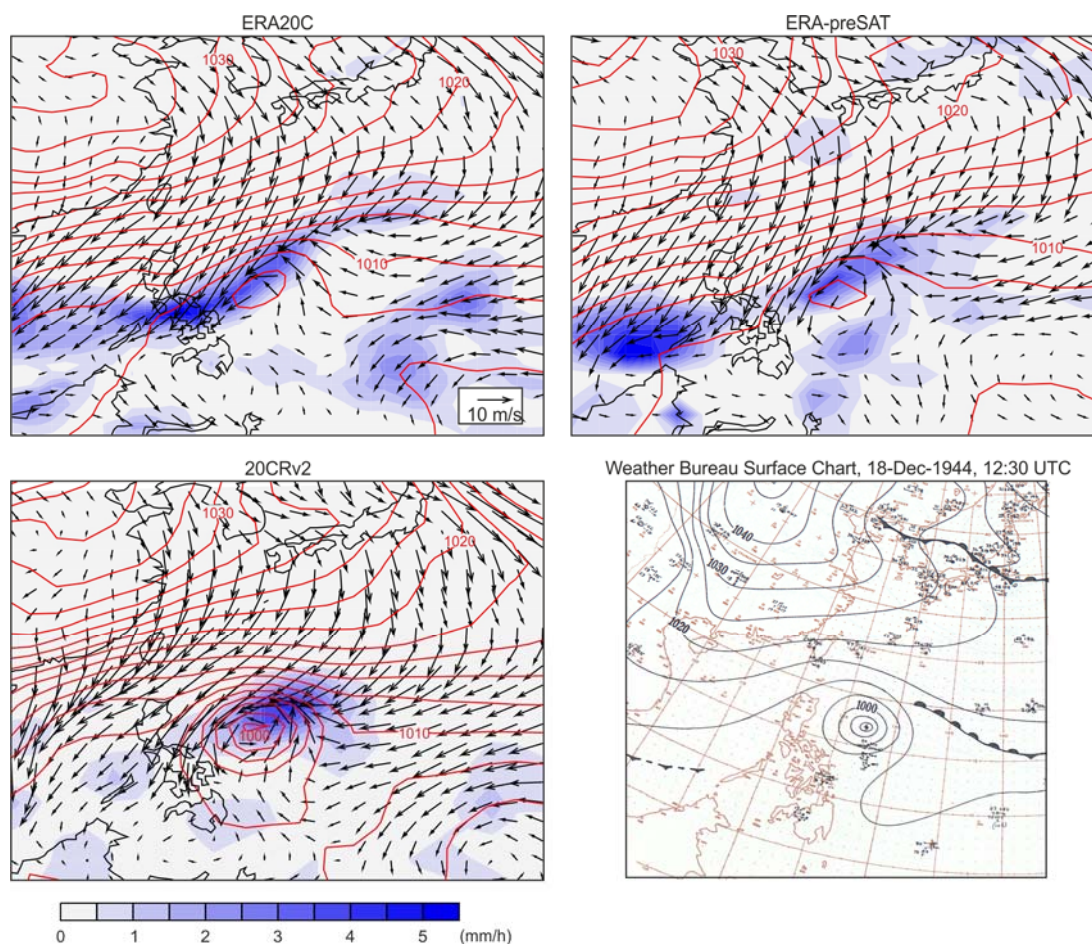only reanalysis that captures QBO from late 1940s up to 1957.

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Fig. 11: Fields of sea-level pressure, 10 m wind, and precipitation on 18 Dec. 1944, 6
UTC from four different reanalyses. The bottom right panel shows the surface
analysis from the Weather Bureau.