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1 **The influence of synoptic circulations and local processes on temperature**
2 **anomalies in three French observatories**

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ABSTRACT

16 The quantification of the relative contribution of the synoptic-scale circula-
17 tion relative to that of local and mesoscale processes concerning the variability
18 of middle latitude temperature anomalies was investigated from 2003 to 2013.
19 Meteorological variables collected from three French observatories and from
20 reanalyses were used. Four weather regimes were defined from sea level pres-
21 sure anomalies from NCEP reanalyses with a K-means algorithm. **No corre-**
22 **lation was found between the daily temperature anomalies and the weather**
23 **regimes and the variability of temperature anomalies within each regime is**
24 **large. It was therefore not possible to evaluate the effect of the large scale on**
25 **the temperature anomalies by this method.** An alternative approach was found
26 with the use of the analogues method: the principle being that for each day of
27 the considered time series, a set of days which had a similar large-scale 500
28 hPa geopotential height field within a fixed domain were considered. The ob-
29 served temperature anomalies were then compared to those observed during
30 the analogue days: the closer the two types of series, the greater the mark of
31 the large scale. This method highlights a widely predominant influence of the
32 large scale atmospheric circulation on the temperature anomalies. It showed a
33 potentially larger influence of the Mediterranean Sea and orographic flow on
34 the two southern observatories. **Low-level cloud radiative effects were also**
35 **found to be able to greatly modulate the variability of the daily temperature**
36 **anomalies.**

37 **1. Introduction**

38 The temperature fluctuations of France and, more generally, Western European are largely con-
39 nected to large-scale weather regimes. However, the processes linking atmospheric variability
40 to surface temperature may vary with the season. Cattiaux et al. (2010) used the geopotential
41 height at 500 hPa to define weather regimes influencing Europe and found that the cold winter of
42 2010 was associated with a large occurrence of the negative phase of the North Atlantic Oscilla-
43 tion (NAO) weather regime. In summer, major heat waves over France and the UK are generally
44 linked to persisting anticyclonic conditions (such as those in 2003) (Cassou et al. 2005; Yiou et al.
45 2008). They may also be linked to Atlantic low pressure, which leads to southerly flows (such as
46 those seen in 2015), with amplification by soil moisture-temperature and boundary layer feedbacks
47 (Schär et al. 2004; Seneviratne et al. 2006; Fischer et al. 2007b; Vautard et al. 2007; Quesada et al.
48 2012; Miralles et al. 2014). Warm winters are linked to a zonal westerly flow (such as in 2007
49 and 2014) (Luterbacher et al. 2007), which can be amplified by land albedo and cloud radiative
50 effects. The role of such amplifying factors was investigated mainly with regional model simula-
51 tions (Zampieri et al. 2009; Stegehuis et al. 2013; Seneviratne et al. 2004; Stefanon et al. 2014),
52 but it was proven necessary to use high resolution observations to validate such an approach, since
53 models seemed to exacerbate the role of these factors over Europe (Cheruy et al. 2014; Bastin
54 et al. 2016). For example, Chiriaco et al. (2014), using a combination of space and ground-based
55 observations and twin simulations, showed that the heat wave that occurred over Northern Europe
56 in July 2006 was linked to specific large-scale conditions favoring a low cloud deficit over this
57 area and was amplified by dry soil, which contributed to about 40% of the anomaly.

58 As for the weather regimes, the large scale flow analogues method was also used to study the sea-
59 sonal variability of surface temperature anomalies over Europe (Cattiaux et al. 2010; Chiriaco et al.

60 2014; Vautard and Yiou 2009; Yiou et al. 2007). Cattiaux et al. (2010) found a positive departure
61 of observed temperatures from flow analogues larger for minimal than for maximal temperatures.
62 They observed the maximal departure over the Alps region. Spatial variability and underestima-
63 tion of the observed temperature anomalies by the reconstructed temperature anomalies suggest an
64 important role of the smaller scale processes concerning temperature anomalies. France is located
65 in a transitional region between the subtropical influence and Atlantic perturbations. It covers
66 an area where climatic models predict a large dispersion in temperature and precipitations due to
67 different sensitivities to local processes (Boé and Terray 2014). For these reasons, it is useful to
68 employ observational data to quantify the influence of large-scale atmospheric circulations relative
69 to those of local processes on the variability of daily temperature anomalies across France.

70 Our study aims to quantify the relative contributions of large-scale atmospheric circulations
71 and of local processes on the variability of temperature anomalies in three observatories located
72 in France. For this, we shall evaluate specific issues : (i) the effect of the weather regimes on
73 daily temperature anomalies by use of the classification of weather regimes defined from sea level
74 pressure (Yiou and Nogaj 2004), and (ii) the capability of local processes to amplify or reduce
75 temperature anomalies by use of flow analogue atmospheric circulations based on the geopoten-
76 tial height at 500 hPa (Yiou et al. 2007). Our analysis is based on a series of meteorological
77 variables (temperature, wind and radiation) observed in three observatories from ROSEA (Réseau
78 d’Observatoires pour la Surveillance de l’Eau Atmosphérique) national network. It is also based
79 on reanalyses (NCEP and ECMWF).

80 The manuscript is organized as follows. In section 2, the three ROSEA observatories, the cor-
81 responding datasets, the large-scale diagnostic and the methodological approach are presented.
82 Section 3 presents the analysis of large-scale conditions versus local processes using flow ana-
83 logues. Conclusions appear in section 4.

84 **2. Data and methodology**

85 *a. Observatories*

86 In this study, we use the surface observations of three observatories (SIRTA (Site Instrumen-
87 tal de Recherche en Télédetection Active), COPDD (Cézeaux-Opme-Puy De Dôme) and P2OA
88 (Plateforme Pyrénéenne de l'Observation de l'Atmosphère)) from the five ROSEA network ob-
89 servatories, located across varied landscapes along a North-South transect across France (Figs. 1a
90 and 1b).

91 1) SIRTA

92 The northern observatory of ROSEA is known as SIRTA (48.7°N-2.2°E and 160 m elevation)
93 (Haeffelin 2005). SIRTA is located on a plateau in a suburban area in Palaiseau, 20 km southwest
94 of Paris (Fig. 1a). It is an instrumental site dedicated to the research into physical and chemi-
95 cal processes in the atmosphere, mainly using remote sensing. Since 2002, observations of pre-
96 cipitation, water vapor, clouds, meteorological variables, atmospheric gases, solar radiation, and
97 wind power have been collected. More details concerning the SIRTA observatory can be found in
98 Haeffelin (2005) or on the following website: <http://sirta.ipsl.polytechnique.fr/sirta.old/>. Quality
99 control and homogenization of the data in an hourly time-resolution was undertaken at SIRTA
100 for the entire observation period (Chiriaco et al. 2014; Cheruy et al. 2013). This project, named
101 SIRTA-ReOBS, provides a single netCDF file with more than 40 variables from 2003 to 2013
102 (<http://sirta.ipsl.polytechnique.fr/sirta.old/reobs.html>).

103 2) CÉZEAUX-COPDD

104 The COPDD observatory is located in the Auvergne region, in the center of France (Fig. 1a)
105 where various in situ and remote sensing instruments continuously measure the atmospheric dy-

106 namics, radiation, atmospheric gases, cloud microphysical variables and aerosols. This observa-
107 tory is composed of three instrumental sites: Cézeaux (at an altitude of 394 m, an urban site,
108 Opme (at an altitude of 680 m), and Puy-De-Dôme (at an altitude of 1465 m). In this study, we
109 use the meteorological variables collected at the Cézeaux site in order to obtain relatively similar
110 terrain across the three sites. The Cézeaux site (45.47°N-3.05°E) is located on a plain on the cam-
111 pus of Blaise Pascal University in Clermont Ferrand. Since 2002, meteorological variables have
112 been measured at this site. More details concerning the COPDD observatory can be found on the
113 following website; <http://wwwobs.univ-bpclermont.fr/SO/mesures/index.php>.

114 3) CRA-P2OA

115 The P2OA observatory is the south most site (Fig. 1a). It is located in the Midi-Pyrenées re-
116 gion and is composed of two sites from the Observatoire Midi Pyrénées (OMP): the Atmospheric
117 Research Center (CRA) in Lannemezan (43.13°N-0.369°E at an altitude of 600 m), and the “Pic
118 du Midi” (43.13°N-0.37°E at an altitude of 2877 m). On this platform, various in situ and remote
119 sensing instruments continuously measure the atmospheric dynamics, surface energy balance, ra-
120 diation, chemistry, aerosol and electricity. Here, we use only meteorological observations at the
121 CRA site which is a rural site located on a plateau in the foothills of the Pyrenees. At the CRA
122 site, standard meteorological observations have been collected since 1995. More details on the
123 P2OA observatory can be found on the website <http://p2oa.aero.obs-mip.fr/>.

124 Given the geographical position of the three observatories, various local processes, such as urban
125 heat islands, cloud cover, and mountain/plain breeze circulations, snow cover, and cloud have a
126 role to play concerning daily temperature anomalies.

127 *b. Data used*

128 In order to base our analysis on a common period and on homogeneous data, data from the
129 Meteo-France standard weather station hosted by one CRA-P2OA of three observatories were
130 used for this study. We employed hourly values concerning temperature and incoming shortwave
131 radiation at 2 m, wind speed and direction at 10 m and rainfall between 2003 and 2013. In the
132 framework of the current study, a similar quality control, homogenization and a combination of
133 variables from various sources as seen in the SIRTA-ReOBS were performed for the meteorologi-
134 cal variables collected in the Cézeaux-COPDD and CRA-P2OA observatories.

135 To characterize the influence of large-scale circulations, we based our study mainly on daily
136 temperature anomalies at 2 m above the surface at the three observatories. To ensure that our
137 anomaly was not affected by seasonal variability in temperatures, it was defined by comparison
138 to the average of the current month. We defined the daily temperature anomalies ($aT(j)$) for the
139 day j by removing the 2003-2013 monthly mean temperature at each observatory. This can be
140 expressed through the following equation:

$$aT(j) = \langle T \rangle_j - \langle T \rangle_{[m,2003-2013]} \quad (1)$$

141 where $\langle T \rangle_j$ is the daily mean temperature for the day j , computed from the mean of hourly
142 temperatures. $\langle T \rangle_{[m,2003-2013]}$ is the monthly mean temperature calculated over the entire pe-
143 riod, and m is the month represented numerically. For example, that $\langle T \rangle_{[1,2003-2013]}$ was the
144 temperature averaged over all the days in January across the period 2003-2013.

145 *c. Large scale analysis diagnostics*

146 1) WEATHER REGIMES

147 Weather regimes enable us to describe large-scale atmospheric circulations in a simple man-
148 ner. With this in mind, we used the classification of weather regimes used by Yiou and Nogaj
149 (2004) and based on the daily anomalies of sea level pressure (SLP) acquired from the NCEP (Na-
150 tional Center for Environmental Prediction) reanalyses ($2.5^\circ \times 2.5^\circ$) (Kalnay 1996). The weather
151 regimes are defined in the Euro-Atlantic region (80°W - 30°E , 30 - 70°N) (Fig. 1b, (the larger black
152 square one) and determined from the “K-means” algorithm, itself computed from the first 10
153 Empirical Orthogonal Functions (EOFs) of seasonal SLP anomalies (Cheng and Wallace 1993;
154 Michelangeli et al. 1995) from 1948 to 2014. The classification used in this study therefore de-
155 pends on the season. Figure 2 gives an illustration of the four weather regimes defined in winter
156 and their occurrence during the 1948-2014 period. We note in this Figure, the positive (reg. 3)
157 and negative (reg. 4) phases of the North Atlantic Oscillation (respectively NAO^+ and NAO^-), a
158 “Scandinavian blocking” (reg. 2), and the “Atlantic Ridge” (reg. 1). Weather regimes appear with
159 a similar frequency with a 27% occurrence for NAO^+ and “Scandinavian blocking”. During the
160 transitional seasons of spring and autumn, a classification into weather regimes is not always ap-
161 propriate due to seasonal shifts (Vrac et al. 2013). Vrac et al. (2013) found that spring frequently
162 corresponds to an early summer or a longer winter, and that autumn is related to a longer summer
163 or earlier winter, making a definition of a regime during these two seasons difficult. Here, we do
164 not consider this classification for transitional seasons. It is also necessary to consider the stability
165 of the regimes during the winter and summer, as they are sometimes not well defined, and only
166 transitory.

167 In order to eliminate the days with ambiguous classification in winter and summer, we use a
168 criterion based on the Euclidean distance and the spatial correlation from the nearest weather
169 regime deducted by the K-means method. We filter the classification by eliminating the days for
170 which the Euclidean distance from the nearest weather regime is larger than 10 hPa and with a
171 spatial correlation with the nearest weather regime lower than 0.15. We eliminated 5.2% (52 days)
172 and 10,8% (109 days) of the total days in winter and summer respectively.

173 Here, we are interested in the influence of the large-scale atmospheric regimes on the variabil-
174 ity of daily temperature anomalies (equation 1) in the three observatories. Figure 3 presents the
175 box plot of daily temperature anomalies in winter and summer for each site and for each weather
176 regime during the 2003-2013 period. This Figure shows that in winter, NAO^+ yields relatively
177 milder temperatures at all sites, while NAO^- and blocking are characterized by relatively colder
178 temperatures at all sites. During Atlantic Ridge conditions, the occurrence of either warmer or
179 colder temperatures than those on average is relatively similar, except at SIRTA, where the winter
180 is mostly mild when this regime prevails. It is however, important to note that specific anomalies,
181 warm or cold, can occur whatever the weather regime at SIRTA, whilst very cold winter days are
182 unlikely to occur at Cézeaux-COPDD or CRA-P2OA when NAO^+ or Atlantic Ridge conditions
183 exist. Extreme temperature anomalies are more frequent at SIRTA, and variability is usually en-
184 hanced, except during NAO^+ . In summer, the weather regimes present almost identically effect
185 on all sites, even if the variability at Cézeaux-COPDD is greater than on the two other sites, and
186 extremes are enhanced. The Atlantic Ridge and NAO^+ have positive daily anomalies on aver-
187 age in winter and summer in all sites, indicating mild and warm temperatures respectively during
188 these two seasons. These results are consistent with those of Yiou et al. (2007) in the fall/winter
189 of 2006/2007. From these results, we can conclude that the weather regimes derived from the

190 SLP data do not explain the daily temperature anomalies at the three observatories in winter and
191 summer according to the weather regimes derived from the SLP data.

192 2) LARGE SCALE FLOW ANALOGUES

193 The slight difference in the anomaly of mean temperatures among the weather regimes in sum-
194 mer, the large variability in the daily temperature anomalies and the fact that the weather regimes
195 are not easily defined in spring and autumn, inspires us to complete the regime approach with the
196 flow analogues method.

197 The method of atmospheric flow analogues was first introduced by Lorenz (1969). Since then, it
198 has found many applications, including weather prediction (Van den Dool 2007). Yiou et al. (2007)
199 used this approach to infer the connection between surface climate variables and atmospheric cir-
200 culation. In this study, we use the flow analogue method developed by Yiou et al. (2007) and used
201 by Chiriaco et al. (2014) and Cattiaux et al. (2010) to study climate variability across Europe. For
202 each day during the eleven year period (2003-2013), we looked for days within the same time se-
203 ries which had similar large-scale atmospheric conditions. For this, we considered field anomalies
204 of geopotential height at 500 hPa from the ERA-Interim (ERA-Interim) reanalyses ($0.75^\circ \times 0.75^\circ$) of
205 ECMWF (Dee et al. 2011), a typical diagnostic tool for large-scale circulations. Analogue days
206 were found by minimizing an euclidean distance and maximizing a Spearman correlation. More
207 details on the flow analogues method can be found in Yiou et al. (2007).

208 By using the flow-analogues to quantify the relative influence of the large and of the local and
209 mesoscale processes on surface temperature anomalies, we considered two nested domains. The
210 first domain covers the Euro-Atlantic region ($80^\circ\text{W}-30^\circ\text{E}$, $30^\circ\text{N}-70^\circ\text{N}$) (Fig. 1b, black square).
211 This domain is also the one used by Cattiaux et al. (2010); Vautard and Yiou (2009); Yiou et al.
212 (2007) and Chiriaco et al. (2014) to establish the link between extreme events (cold waves, heat

213 waves and drought) and large scale conditions over Europe. The second domain covers the area
214 21°W - 30°E , 30 - 60°N (Fig. 1b, white square). Compared to the larger domain, this smaller domain
215 (mesoscale) gives more weight to the Mediterranean sea influence on synoptic circulations than
216 does the Atlantic Ocean.

217 For each day in our studied period and for each domain considered, we kept a maximum of ten
218 analogues, which satisfied the following two criteria: (i) the Spearman spatial correlation had to
219 be greater or equal to 0.6, ensuring the quality of the similarity, and (ii) they should not be closer
220 than 6 days from the current day, in order to ensure that the analogues were independent of the
221 target day (assuming a decorrelation time of 3 days before and 5 days after the target day). These
222 criteria eliminated 6,4 % (around 256 days) and 3 % (around 119 days) of days respectively in
223 terms of the large and small domain. The scores are higher in winter, spring and autumn than in
224 summer for both domains. We found 134 and 54 unselected days respectively for the large and
225 small domain in Summer.

226 *d. Analysis protocol*

227 To quantify the contribution of local processes and large scale circulations at each site, we com-
228 pared the observed temperature anomalies to the temperature anomalies observed during the ana-
229 logue days. Figure 4 illustrates this approach for the year 2007 with analogues of circulation
230 computed over the small domain. It shows that, for all observatories, the analogues reproduced
231 the observed temperature anomalies quite well, but they also presented great variability between
232 analogues. For certain days, the analogues could not capture the amplitude of the observed anoma-
233 lies, as can be seen in the example from 17 to 20 January 2007 on all sites, February 2007 at SIRT
234 and Cézeaux-COPDD, at the end of August 2007 at CRA-P2OA, and at the end of April 2007 at
235 SIRT. A smaller standard deviation of the ten anomalies of analogous days combined with an

236 average closer to the temperature anomaly of the day in question means that the large scale **ex-**
237 **plains the anomaly**. In our study, we investigated whether this departure from the observed series
238 relative to the envelope defined by the atmospheric conditions on analogue days **can be explained**
239 **by** local processes.

240 Weather regimes were used to describe and better understand the large-scale influence (see in-
241 dications of the regimes in Fig. 4).

242 **3. Analysis of large scale conditions versus local processes**

243 In order to estimate the influence of the Mediterranean Sea relative to the Atlantic Ocean at the
244 three sites, we first evaluated the ability of the analogues to represent the observed series using
245 the two different domains described above. Afterward, the difference between the observed series
246 and the temperature anomalies of the analogues was quantified by the definition and the use of an
247 **anomaly index**. Finally, we focused on specific periods during which the difference was larger than
248 1.5 °C, tried to identify the **relevant processes** and discussed the **relative** contribution of large-scale
249 and local processes.

250 *a. Sensitivity to the Mediterranean Sea*

251 Figure 5 presents the correlation between observed anomalies and those deduced from flow
252 analogues in the large and small domains (Fig. 1b) for each site and for each season. All observed
253 daily temperature anomalies for each season are correlated with those of their 10 analogue days.
254 Thus, for each season of each year from 2003 to 2013, we have one correlation coefficient. This
255 Figure points out larger correlation coefficients in the small domain than in the large domain. This
256 is obvious for the two southern observatories whatever the season, whereas higher correlation
257 coefficients across the small domain are observed only in summer and spring for SIRTÀ. This

258 shows that SIRTA is more influenced by large-scale air masses coming from the Atlantic than by
259 mesoscale processes induced by orography and the presence of the Mediterranean Sea, which can
260 strongly influence the weather across southern France (e.g Ducrocq et al. (2008)).

261 We found a large spatio-temporal variability in the correlation coefficients. CRA-P2OA pre-
262 sented on average the lowest correlation coefficients for the two domains (0.52 and 0.35 respec-
263 tively for the small and large domain) compared to the two other sites (for the small domain,
264 Cézeaux-COPDD and SIRTA had respectively 0.55 and 0.57 and for the large domain, 0.38 and
265 0.46 respectively). This difference can be due to its proximity to the Pyrenees, where local pro-
266 cesses linked with topography exist: for example, local convection or plain-mountain breeze circu-
267 lations are more frequent in summer. The two cases of very small correlation coefficient with the
268 small domain (shown in Fig. 5a-b-c on the left bottom with green and black colors) were observed
269 in autumn 2011 at each site, during the winter of 2006 at SIRTA, and during the winter of 2008 at
270 CRA-P2OA and Cézeaux-COPDD. The autumn of 2011 was exceptionally warm. It was indeed
271 the second warmest autumn during the period 1948-2011, and after 2006, according to Cattiaux
272 and Yiou (2012). Cattiaux and Yiou (2012) found that the flow analogues underestimated the am-
273 plitude of the seasonal temperature anomaly in Europe during this specific season. This suggests
274 that global warming plays an important role by increasing the concentration of greenhouse gases:
275 the advected air mass is warmer, but it can also enhance local feedbacks.

276 In the following section, we evaluate the flow analogues approach by considering only the
277 smaller domain, in order to quantify the influence of local processes on the climate variability
278 at the three sites.

279 *b. Large scale influence*

280 We have attempted to better quantify the relative contribution of the large scale versus local
281 processes on the amplitude of temperature anomalies. Since the average signal of the analogues
282 has lower fluctuations than the observed series by construction, we introduce I_m , a new index
283 which will allow two normalized observation and analogue series to be compared.

284 This index I_m , defined for each month m , represents the normalized monthly average anomaly
285 $\langle aT(j) \rangle_m$ relative to the standard deviation of the 2003-2013 daily anomalies for the given
286 month m . We compute I_m with:

$$I_m = \frac{\langle aT(j) \rangle_m}{\sqrt{\langle (aT(j) - \langle aT(j) \rangle_{[m,2003-2013]})^2 \rangle_m}}, \quad (2)$$

287 where $\langle aT(j) \rangle_{[m,2003-2013]}$ is the average anomaly of temperature of the current month m during
288 the period 2003-2013. In other words, the red line in Fig. 4 is averaged monthly and divided by the
289 standard deviation computed from the monthly anomalies for the period 2003-2013. Concerning
290 the analogue signal, the same definition of the index is applied using all observed anomalies in the
291 analogue days.

292 Figure 6 represents the time series of this index across the period 2003-2013. The flow analogues
293 reproduce the variability of surface temperature anomalies particularly well. The correlation coef-
294 ficients between I_m for observations and analogues are 0.80 for SIRTAs, 0.85 for Cézeaux-COPDD
295 and 0.86 for CRA-P2OA. This means that the large scale actually plays a predominant role in
296 creating the temperature anomaly variability on monthly scales, which is not surprising.

297 In Fig. 6, one may note the spatio-temporal variability of I_m in the three observatories. The years
298 2003 and 2011 were the warmest years on every site for the period 2003-2013, whereas the coldest
299 year on every site was that of 2010 with negative I_m for every month.

300 While the general trend is well captured by I_m for analogue days, the magnitude of certain
301 events is not reproduced. For example, February 2007 was exceptionally warm with I_m larger
302 than 1.7 at SIRT A and Cézeaux-COPDD according to observations. This peak in temperature
303 is not reproduced by flow analogues with an index of around 0.5 (Fig. 6) when using the small
304 domain, and is even negative when using the large domain (not shown). The large anomaly is not
305 observed at CRA-P2OA. The spatial variability of temperature anomalies during this winter and
306 the difference between observed anomalies and analogues allow us to hypothesize that specific
307 synoptic scale features leading to local anomalies are not resolved by the analogue approach alone
308 and that local processes may have played a specific role at each site during this period.

309 *c. Analysis of specific events during winter 2007*

310 We focused on the winter of 2006/2007 in order to further investigate the contribution of large
311 and local scale processes in the spatio-temporal variability of daily temperature anomalies in the
312 observatories. Note that winter 2007 appears to be the warmest of our study period: it was the sec-
313 ond warmest winter in France since 1959 according to climatology established by Meteo-France.

314 Figure 7 shows the time series of daily temperature anomalies for the winter of 2006/2007 from
315 observations and analogues. It thus corresponds to a zoom of Fig. 4 in January and February
316 2007. During this period, two regimes, “NAO+” and “Atlantic ridge” are persistent. “NAO+” is
317 associated with a southwesterly flow over Northern Europe (Michelangeli et al. 1995). We showed
318 in section 2c that the two regimes, “NAO+” and “Atlantic Ridge” are usually the warmest in winter
319 at all three sites. These results are consistent with those of Yiou et al. (2007) for the exceptionally
320 warm 2006/2007 fall/winter. The regime NAO⁻ appears between 22 and 26 January, with negative
321 anomalies at all sites. Snow was observed at SIRT A on 23 January, and from 23 to 25 January at
322 CRA-P2OA and Cézeaux-COPDD.

323 We focused on specific warm events during the winter of 2007 to investigate the role of lo-
324 cal processes on the spatio-temporal variability of daily temperature anomalies. We will further
325 analyze two periods /dates: the period 17 to 19 January and a single day: 16 February 2007.

326 1) 17-19 JANUARY 2007 CASE

327 The period from 17 to 19 January houses the warmest anomalies of the month of January 2007 at
328 all sites (Fig. 7) with spatial variability in the amplitude: the southern site (CRA-P2OA) presents
329 the lowest daily temperature anomalies compared to the two other sites (warmest anomaly of 9.4,
330 10 and 7.2 °C at SIRTA, Cézeaux-COPDD and CRA-P2OA respectively, on 18 January 2007).
331 The observed positive temperature anomalies are higher than those of analogue days for the whole
332 17-19 January period at SIRTA and Cézeaux-COPDD and only at CRA-P2OA for the 18 January.
333 Despite the spatial variability in the temperature anomalies, 18 January 2007 presents an anomaly
334 on a large-scale and one can wonder why the anomaly's amplitude of such a large-scale event is
335 not reproduced by any of the analogue days.

336 To answer this question, the large-scale meteorological situation of analogue days is verified
337 using satellites and ERAI reanalyses and local effects are analyzed based on the meteorological
338 history of the surface measurements and radiosoundings. The meteorological history provides
339 a view of the atmospheric conditions of previous days on a local scale. We consider therefore
340 the diurnal cycles on 18 January 2007 and on the two previous days (16 and 17 January 2007)
341 to point out the effect of the “local meteorological history” at each site. Similarly, the “local
342 meteorological history” of the five best analogue days on the 18 January 2007 is presented. For
343 example, if the 20 December 2011 is one analogue day for the 18 January 2007, the time series
344 from 18 to 20 December 2011 are displayed.

345 The large-scale circulation is the NAO⁺ regime on the 17 and 18 January, and “Atlantic ridge”
346 on 19 January (Fig. 7). Figure 8 presents the wind speed and direction at 600 hPa from the ERAI
347 reanalyses. It shows an increasing westerly wind over France during the 16-18 January period.
348 The five most accurate analogues are generally coherent with an increasing wind speed from 17 to
349 18 January and show similar wind directions. However, wind speed varies from one analogue to
350 another.

351 The reflectance in the visible channel at 0.6 μm of MeteoSat Second Generation (MSG) at 1300
352 UTC on 18 January 2007 is shown in Fig. 9a. Large cloud cover over the North Atlantic and
353 Europe was observed with a window of clear sky over the Mediterranean basin, the South of Spain
354 and the Pyrenees region. Similar cloud cover was also observed on 17 and 19 January 2007 (not
355 shown). The method of Wang and Rossow (1995) was applied to the vertical profile of relative
356 humidity from the radiosoundings at Trappes on 18 January (Fig. 9b) to define the cloud base
357 height. Wang and Rossow (1995) used among other criteria, 87% and 84% as maximum and
358 minimum relative humidity thresholds respectively and relative humidity jumps exceeding 3% at
359 cloud-layer top and base to characterize a cloud-layer. With this method, we find in Fig. 9b that
360 on the 18 January, cloud cover was dominated by low-level clouds with a base not exceeding 700
361 m in height at 1100 UTC. At 2300 UTC, cloud cover descended and thickened. Based on the
362 Meteo-France weather service station, drizzle was observed that night, with 0.8 mm falling at this
363 site. Combining the satellite image and vertical profiles of relative humidity, we find that these low
364 clouds are stratocumulus clouds associated with the stable atmospheric conditions in the South of
365 Europe linked to the NAO⁺ regime. Indeed, the stratocumulus clouds occur widely over Europe in
366 January, according to Hahn and Warren (2007). A similar analysis of the vertical profile of relative
367 humidity for the five most accurate analogue days (Fig. 9b) shows that the 18 January 2007 was
368 the cloudiest day: either there was no cloud cover (analogue day number 3), or there was cloud

369 cover which disappeared between 1100 and 2300 UTC (analogue day number 1), or much thinner
370 cloud cover (analogue days number 4 and 5). We can expect an effect due to this cloud layer on
371 the 18 January since it impacts the radiative budget at the surface at SIRT A and Cézeaux-COPDD.

372 The meteorological history of the 18 January and its five most precise analogue days was an-
373 alyzed with surface measurements. The large scale cloud cover, discussed previously (Fig. 9)
374 impacts incoming solar radiation (ISR) (Fig. 10). The ISR measured at the surface increases from
375 north to south, with very cloudy conditions at SIRT A for every day and almost no reduction of
376 ISR at CRA-P2OA. The integration of ISR across the three days defining the meteorological his-
377 tory period (not shown) demonstrates that there is an obvious lack of ISR for the observed days
378 compared to the analogue days at SIRT A and Cézeaux-COPDD, contrary to CRA-P2OA.

379 Figure 10 presents the time series of temperature, incoming shortwave radiation at 2 m, wind
380 speed and direction at 10 m above the ground. Cloud cover also clearly impacts the diurnal cycle of
381 2m-temperature (Fig. 10); Low cloud cover at SIRT A reduces the cooling of the earth and smooths
382 the diurnal temperature cycle. This is also the case at Cézeaux-COPDD, on 18 January. On the
383 contrary, a large diurnal temperature cycle can be observed at CRA-P2OA on most of the days,
384 especially during the period 16-18 January.

385 At SIRT A, the westerly wind direction at the surface is consistent with the synoptic wind (Fig. 8).
386 The wind direction at Cézeaux-COPDD is very variable but maintains a westerly direction on
387 average, whereas a clear effect of the mountain range can be observed on 16, 17 and some of 18
388 January at CRA-P2OA, with some slope winds with a north-eastern direction during the day and
389 a southern direction during the night, a sign of the plain-mountain diurnal circulation. Figure 10
390 shows the diversity of the conditions observed during the analogue days at CRA-P2OA, which
391 makes the comparison difficult. Among the five most accurate analogue days, only three are cloud-
392 free. All of them present a reversal of the wind direction twice a day. This is characteristic of the

393 slope wind, which seems to play an important role and blurs the comparison of the diurnal cycle.
394 During winter, a lack of cloud cover may allow weak convection over mountains, and certainly
395 greater radiative cooling at night. This southerly mountain breeze during the night advects cool
396 air from the mountains and is associated with low temperatures at night in the diurnal cycle. The
397 mountain breeze which occurs during the NAO⁺ regime could then reduce the positive temperature
398 anomaly tendency associated with this regime. The meteorological history of 18 January shows a
399 slope wind regime until noon, when a clear westerly wind settles at the surface. From that moment,
400 the temperature clearly increases, and remains high during the night, with no mountain breezes,
401 between 18 and 19 January. The daily mean temperature then leads to a larger positive temperature
402 anomaly compared with the analogue days with slope winds lasting all day.

403 From these large and local scales analyses of the observed days and their analogue days, we
404 can ascribe this positive temperature anomaly to a large-scale event observed on the three sites.
405 The NAO⁺ regime, which advects mild temperatures from the Atlantic ocean, is characterized
406 by the warmest temperature anomaly in winter (Fig. 3). The flow analogue method shows some
407 limitations however representing this event. The cloud layer is particularly low and deep, and lasts
408 for three days over the northern part of France, whereas nothing in the meteorological history of the
409 analogue days presents such conditions. This cloud cover could imply a warming radiative effect
410 over SIRT A and Cézeaux-COPDD during the 17-19 January period, which would amplify the
411 positive anomaly due to what is already mild air advection. While the low cloud cover observed
412 during this event is not a local effect, its radiative interaction with the surface is dependent on
413 surface temperature and can be considered as a local effect.

414 In conclusion, it seems that this abnormal warm event stands out from the analogue days, for
415 various reasons- at SIRT A and Cézeaux-COPDD in the first instance and then at CRA-P2OA.
416 The large-scale positive anomaly associated with the NAO⁺ regime is amplified at SIRT A and

417 Cézeaux-COPDD by the warming radiative effect of an unusually low cloud cover occurring over
418 the two sites during the 11 year period. This event, lasting for three days, lead to warmer anomalies
419 than on analogue days. Meanwhile, in CRA-P2OA, the absence of clouds lead to a down-valley
420 wind regime which tends to cool the air at night and to reduce the NAO⁺ regime warm anomaly.
421 The down-valley wind was observed on 18 January until midday and did not occur the following
422 night. This lead to higher nocturnal temperatures and warmer daily temperature anomalies than on
423 analogue days the following night. These results show that radiation and cloud cover are important
424 predictors of daily temperature anomalies in winter at this observatory.

425 2) 16 FEBRUARY 2007 CASE

426 16 February 2007 is an example of a case where the temperature anomaly largely exceeded the
427 range of the flow analogues at a single site. A strong and warm anomaly of 12.3 °C was observed
428 at CRA-P2OA on that day, while all analogues showed an anomaly below 8 °C (Fig. 7). At the two
429 other observatories, the temperature anomaly on this day lay within the envelope of the analogues.

430 The synoptic atmospheric conditions on 16 February were forced by the presence of very low
431 pressure centered over Iceland, and its associated thalweg extending from the island towards the
432 south, near Spain and Morocco. This situation, which often announces the arrival of a front,
433 generated a south-southwesterly wind regime in altitude, bringing dry and warm air from the
434 south. The wind at 600 hPa across the three sites and deduced from the reanalyses of the European
435 Center is shown in Fig. 11 for 16 February and for its analogous days. The analogues have the
436 same types of southwesterly wind regime across the three sites. This situation generally leads to a
437 positive temperature anomaly due to the southern origin of the air mass in many such cases. For
438 this reason, on average, the envelope of the analogues shows a positive temperature anomaly at all
439 sites (Fig. 7).

440 Southerly winds over the ridge of the Pyrenees correspond to the typical situation of the so-
441 called foehn phenomenon: the East-West orientated mountain ridge is an obstacle for the flow,
442 which can be partially blocked in the lower layers and which can bypass the ridge, with the flow
443 splitting at its sides, or/and passing over and through it across the mountain passes (Scorer 1949,
444 1953, 1955; Scorer and Klieforth 1959; Seibert 1990; Ólafsson and Bougeault 1997; Jiang et al.
445 2005). The adiabatic descent of air in the lee, usually occurring together with the flow over the
446 mountain, is associated with a typical drying and warming in the lower lee air layers on the French
447 side ('foehn effect').

448 One of the most important governing variables for this phenomenon is the upwind wind profile,
449 and particularly the upwind component, which is perpendicular to the ridge: the larger this com-
450 ponent, the easier it is for the flow to go over the mountain and generate the foehn effect (Seibert
451 1990). For the Pyrenees in the vicinity of the CRA-P2OA site, we evaluate the cross-component
452 at 210° azimuth ($\pm 10^\circ$): that is, a wind with this direction (which is very similar to a southerly
453 wind) travels exactly transversely to the ridge, on a 150 km horizontal scale. This direction is also
454 aligned with the main Aure Valley, which is situated south of the CRA-P2OA observatory and
455 North-South orientated. Figure 12a shows the upwind profiles of the cross-ridge component (pro-
456 jection of the wind on the 210° axis), for 16 February and for all analogues, at 0000 UTC. These
457 are deduced from the radiosoundings launched daily from Zaragosa in Spain, which is located
458 about 150 km south of the ridge of the Pyrenees, and 200 km from the CRA-P2OA site. These
459 profiles confirm the potential to generate the foehn effect at CRA-P2OA for most of the days
460 shown, as this component is positive for most cases above 1000 m. It also reveals that 16 February
461 is the case with the strongest 210° upwind component between 1000 m and 6000 m, especially
462 below 3500 m, making it the most favorable case for a strong foehn event (the highest peak in the

463 Pyrenees is at 3400 m). Figure 11 also shows that the upwind wind increased significantly during
464 the day.

465 Figure 12b presents the visible image of MSG at 1500 UTC on 16 February 2007. This day was
466 marked by large cloud cover over the western Atlantic and northern Europe, and a clear sky above
467 the Mediterranean basin and eastern Europe. Cloud cover over the Pyrenees shows that the sky
468 was clear in Spain and in the lee of the mountain (where CRA-P2OA is situated). Further to the
469 north, a cloud with a well-defined southern border, typical of the upward branch of a mountain
470 wave, can be observed, and is usually associated with foehn and southerly overpassing flows. The
471 clear sky in Spain reveals a “dry foehn” as opposed to some cases, where clouds are blocked on
472 the Spanish side, with some rain that can contribute to the drying and warming effect of the air in
473 the lee on the French side. This means that on 16 February, air mass was generally very dry on
474 the large-scale, a fact which is confirmed by the radiosoundings of Zaragoza, Bordeaux (Atlantic
475 French coast), Trappes (close to Paris), and the synoptic situation discussed before. The soundings
476 of Trappes at 1100 and 2300 UTC show very dry and warm air between 800 m and 4000 m. Above
477 this altitude, fine medium clouds (of about 500 m) are observed (not shown).

478 We can now consider the observations at the surface of the different observatories. Figure 13
479 presents the evolution of the meteorological variables observed close to the surface on 16 February
480 2007, and of its analogues. The most striking feature is found in the surface wind at CRA-P2OA:
481 for all the analogues, the wind at the surface is southerly during the night and northerly during
482 the day. This, along with the low associated wind speed (below 6 m s^{-1}), is the influence of the
483 mountain-plain diurnal circulation. That is to say, although the upwind flow is from the south, and
484 sometimes has a strong wind speed (Fig. 12a), this does not prevent the plain-mountain circulation
485 from settling during those analogue days. It is actually quite classic, with the southerly wind kept
486 at a higher level. Note that this does not prevent the foehn effect (warming and drying in the

487 lee), or the warmer local temperature that can be found at this site relative to the other sites. On
488 16 February, however, the wind at the surface of CRA-P2OA remained southerly all day, with
489 the wind speed increasing during the day, by up to 10 m s^{-1} at times. This means that for this
490 specific day, the upwind flow was strong enough to be able to create a downslope wind throughout
491 the entire day in which case, the warming and drying effect in the lee is still larger. This is
492 consistent with Fig. 12a, which shows the singularity of this day in terms of upwind conditions.
493 It probably explains most of the temperature anomalies found at CRA-P2OA, which exceed the
494 usual anomalies found in analogous synoptic situations (Fig. 7).

495 At Cézeaux-COPDD, this synoptic situation does not lead to a marked anomaly, but the general
496 dry and warm air leads to a large diurnal increase. The night of 16 to 17 February may have been
497 influenced by a small foehn effect, in the presence of westerly winds (typically occurring in the
498 “Chaine des puys” mountains to the west of the site). The air temperature does not decrease
499 much, and the wind continues to arrive from the west. At SIRTÀ, the wind at the surface is
500 easterly, surprisingly, while the sounding at Trappes shows a strong southerly flow down to the
501 lowest levels of the atmosphere. This weak easterly wind at SIRTÀ seems unconnected to the
502 warm, dry southerly air above, and could explain the relative lower temperature found on 16
503 February (relative to its analogues).

504 This event shows how sub-mesoscale processes linked with orography can amplify a temperature
505 anomaly which is first of all forced at the synoptic scale. This specific type of amplification has
506 been previously observed by Takane and Kusaka (2011) in Japan in the summer.

507 **4. Summary and Conclusions**

508 This study aimed to evaluate the relative contribution of large scale atmospheric circulation and
509 more local processes to daily temperature anomalies over a North-South transect of France. The

510 study was based on the observations of meteorological variables on three observatories and on
511 NCEP and ECMWF reanalyses. The flow analogues methods was used in particular to diagnose
512 the fingerprint of the large scale synoptic circulation concerning the temperature anomaly, and to
513 highlight the potential role of local processes in inhibiting or amplifying the anomaly.

514 The analysis of weather regimes over the Euro-Atlantic region shows that the large-scale atmo-
515 spheric circulations have an important influence on the daily temperature anomalies at the three
516 observatories in winter. The “NAO⁺” and “Atlantic Ridge” appear to be the warmest regimes in
517 this season. While the influence of the four weather regimes on daily temperature anomalies does
518 not statistically differ at the three observatories in the summer due to strong variability within each
519 regime, extreme anomalies are associated with one or two regimes at all observatories except for
520 that of SIRT A.

521 The approach of flow analogues over two different domains shows that SIRT A is less affected
522 by the mesoscale processes formed around the Mediterranean Sea than are the two other observa-
523 tories, which is not surprising considering its northern location.

524 The atmospheric circulation analogue method demonstrates the large correlation between a
525 monthly temperature anomaly index calculated from the observed series and that which is pro-
526 vided by the representation of the analogues. This highlights the predominant role played by the
527 large-scale situation in the temperature anomalies. Sometimes, however, the amplitude of the
528 monthly temperature index is not captured by the flow analogues and presents a large spatial vari-
529 ability between the three observatories. It is suggested that these discrepancies are related to local
530 processes. Two specific events revealed in the warmest winter in the period 2003-2013 are further
531 analyzed to test this hypothesis: 1/ the 17-19 January 2007 event which had the strongest posi-
532 tive temperature anomaly at the two northern observatories (SIRT A and Cézeaux-COPDD) and,

533 2/ the 16 February 2007, for which only CRA-P2OA presented a very large positive temperature
534 anomaly, found beyond the signal of the set of analogues.

535 From the analysis of these two events, the impact of several local processes have been identified:

536 1/ the local impact of non-local cloud cover during westerly wind conditions in winter: low-level
537 clouds have been shown to increase the positive temperature anomaly at SIRTÀ and Cézeaux-
538 COPDD in these conditions, partly due to the positive radiative green-house effect of the clouds.

539 2/ the orographic impact: CRA-P2OA and Cézeaux-COPDD are both in proximity to mountains
540 and are frequently impacted by either the foehn or slope wind effect. In a weak large-scale situa-
541 tion, the slope breeze easily settles at CRA-P2OA, and can transport cool air from the mountain
542 during the night in winter. Foehn events observed at both the CRA-P2OA and Cézeaux-COPDD
543 sites with southerly and westerly wind conditions respectively, can amplify positive temperature
544 anomalies, originally forced by the large scale.

545 The analysis of two specific events reveals that some local processes are able to modulate the
546 trend of the daily temperature anomaly driven by the large-scale atmospheric circulation. How-
547 ever, such a phenomenological approach remains difficult, since the understanding of one event
548 necessitates the analysis of the meteorological history of not only the event itself, but also of its
549 analogue days. To investigate the impact of local processes, a systematic study of all cases in
550 which observations differ from analogue days would be necessary.

551 Departures between observed local anomalies and analogues might not only be due to local
552 processes but also to differences between the observed event and its analogues on the synoptic
553 scale, which would not be adequately resolved by the classical analogue approach employed. A
554 possibility for the investigation of this is the combining of different variables in the analogues
555 method (vorticity, water vapor, temperature, wind), even if this would require much longer series
556 in order to ensure a large enough number of analogues for each day.

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679 *J. Climate*, **22**, 4747–4758.

680 [FIG. 1 about here.]

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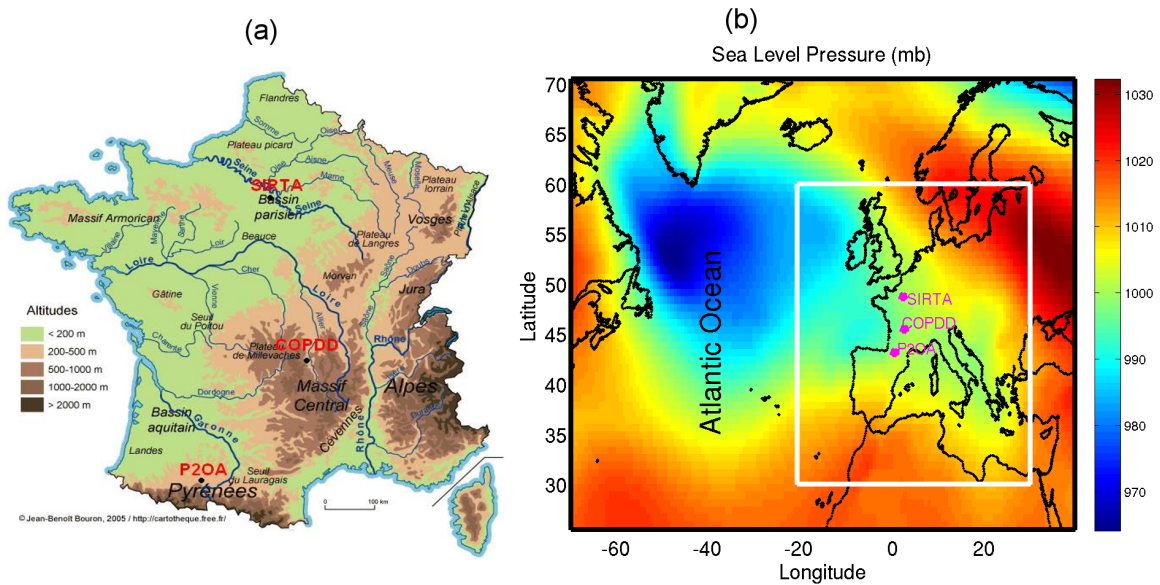
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 724 “NAO⁻” (cyan) “Atlantic Ridge” and (red) “Blocking”. 42

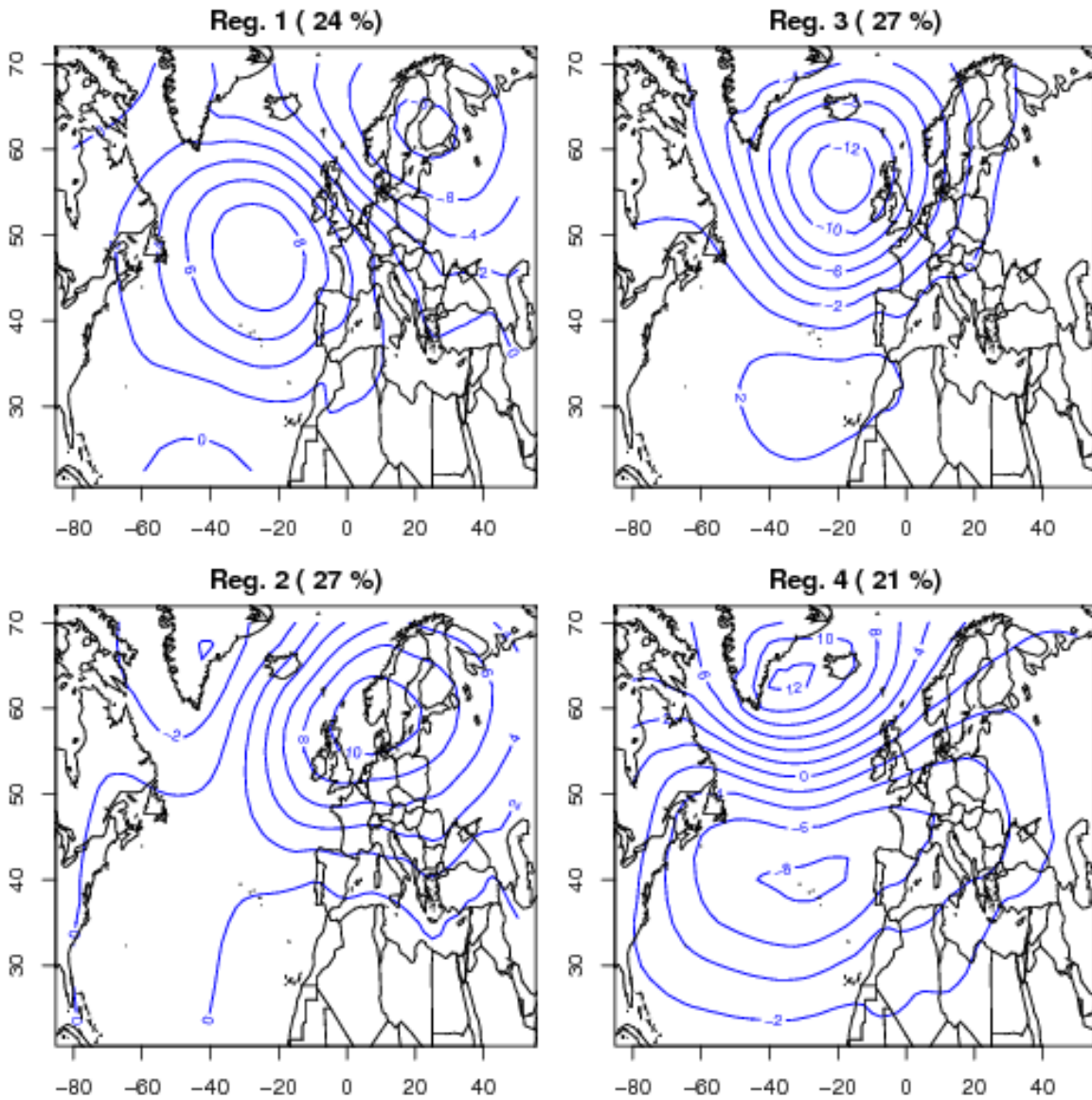
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 735 heights. No radiosoundings at 2300 UTC for the analogue days number 2 and 3. 44

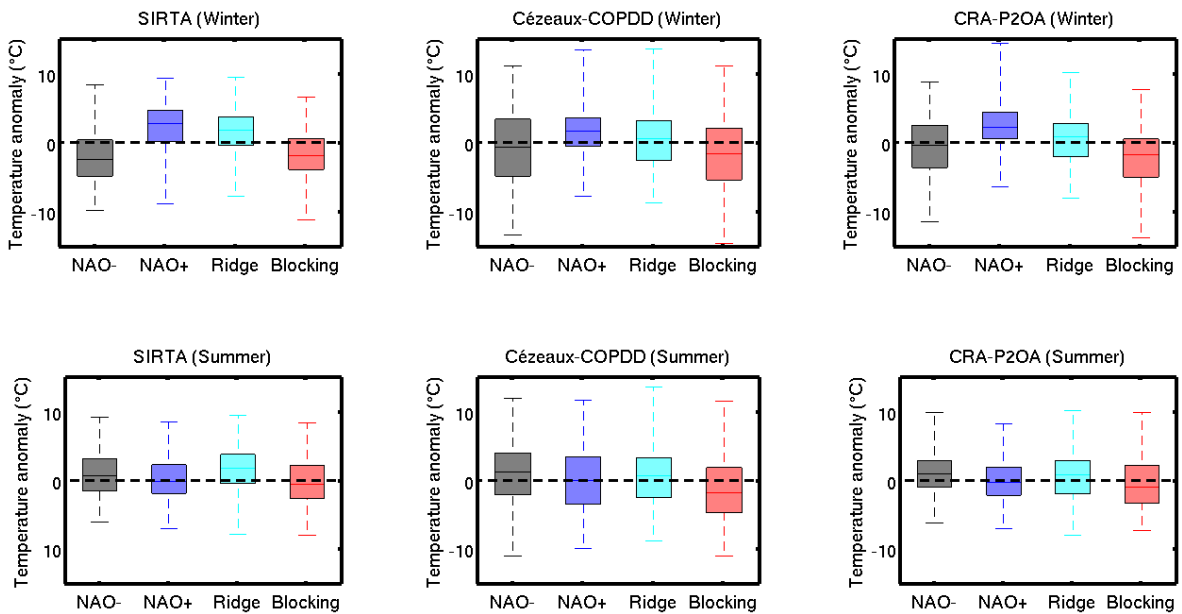
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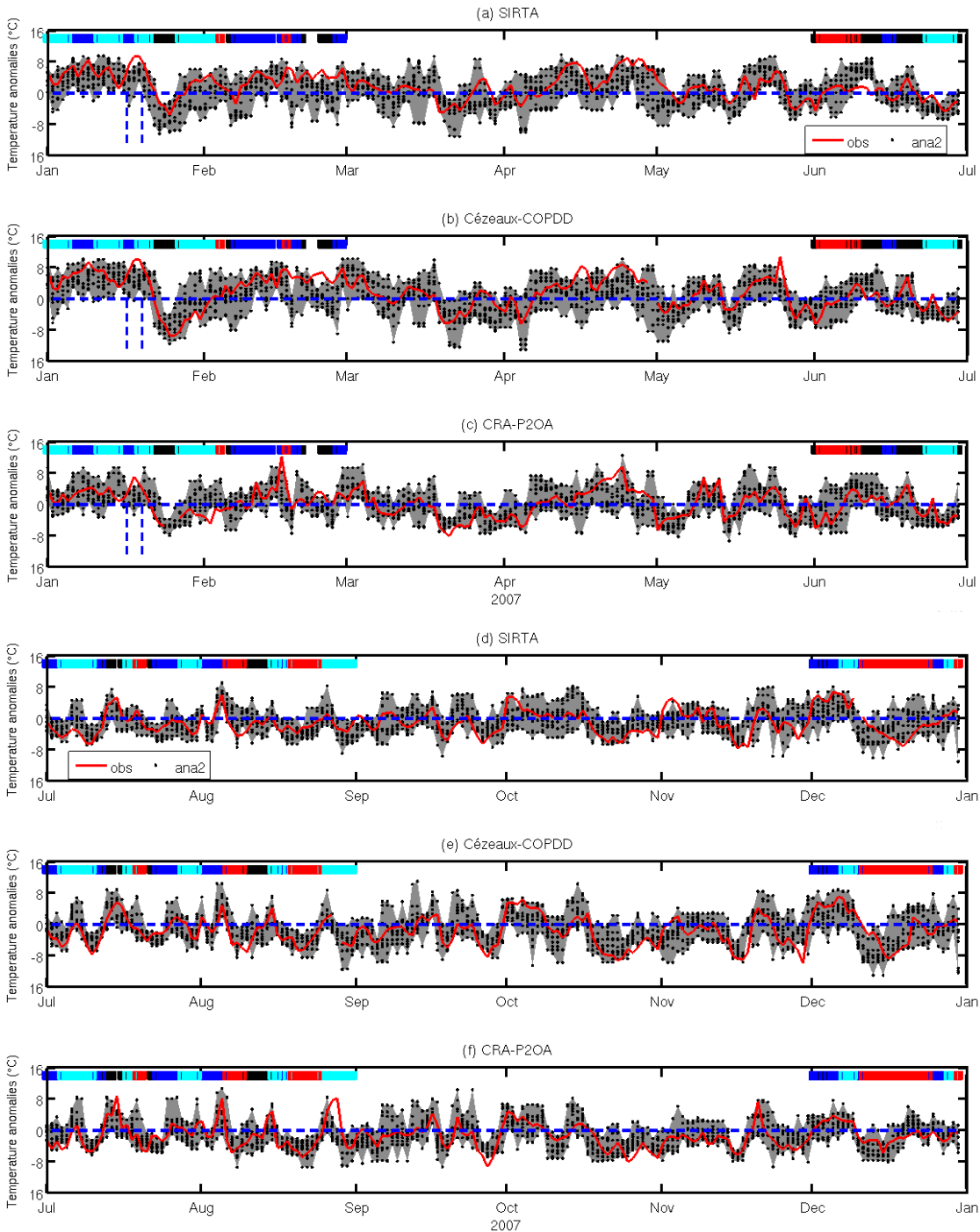
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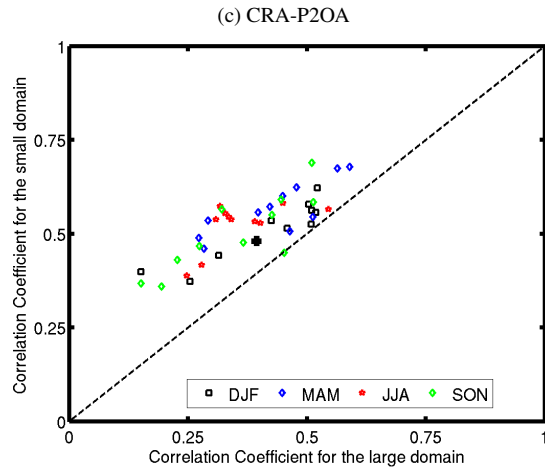
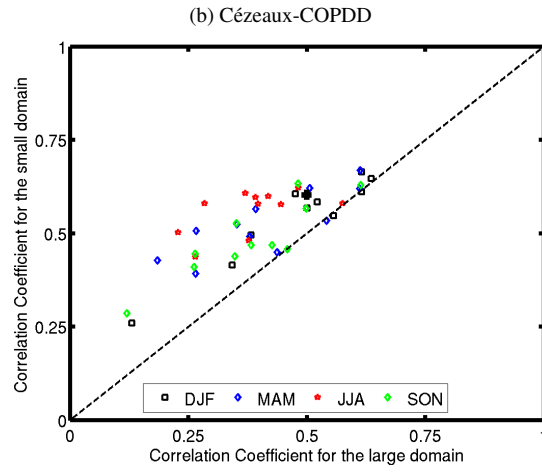
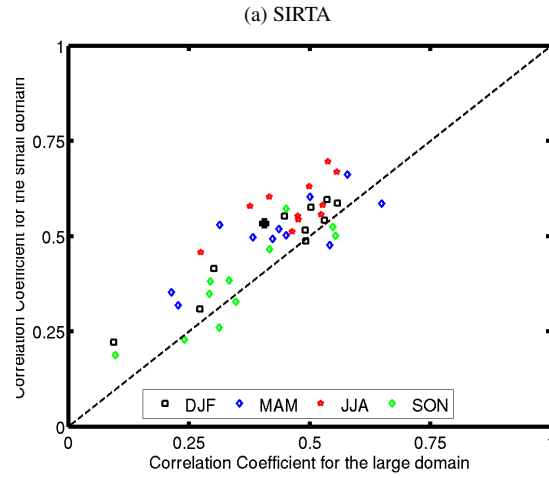
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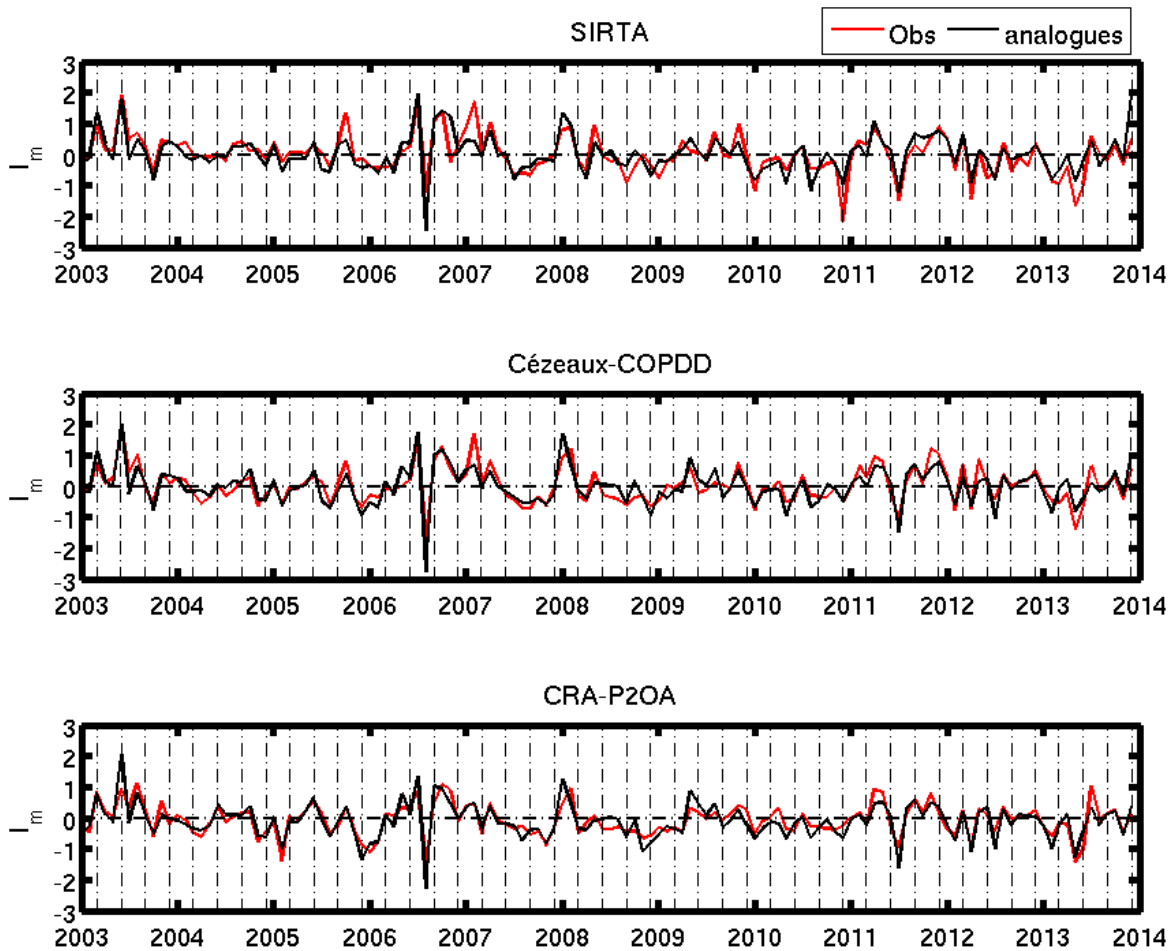
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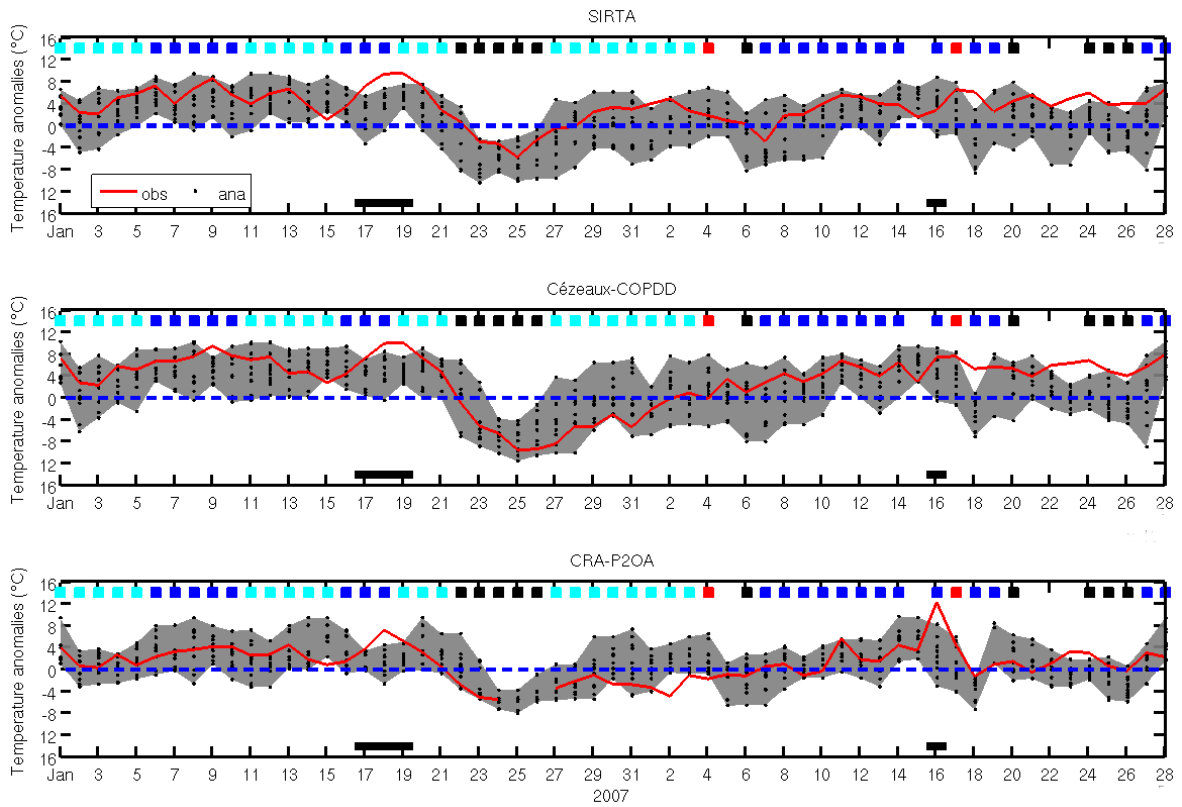
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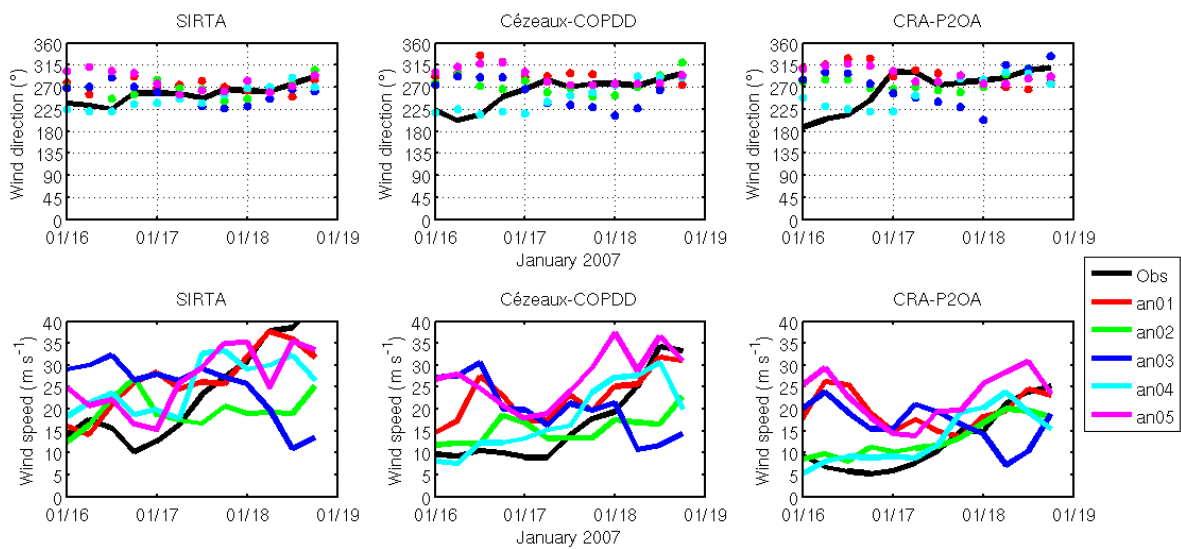
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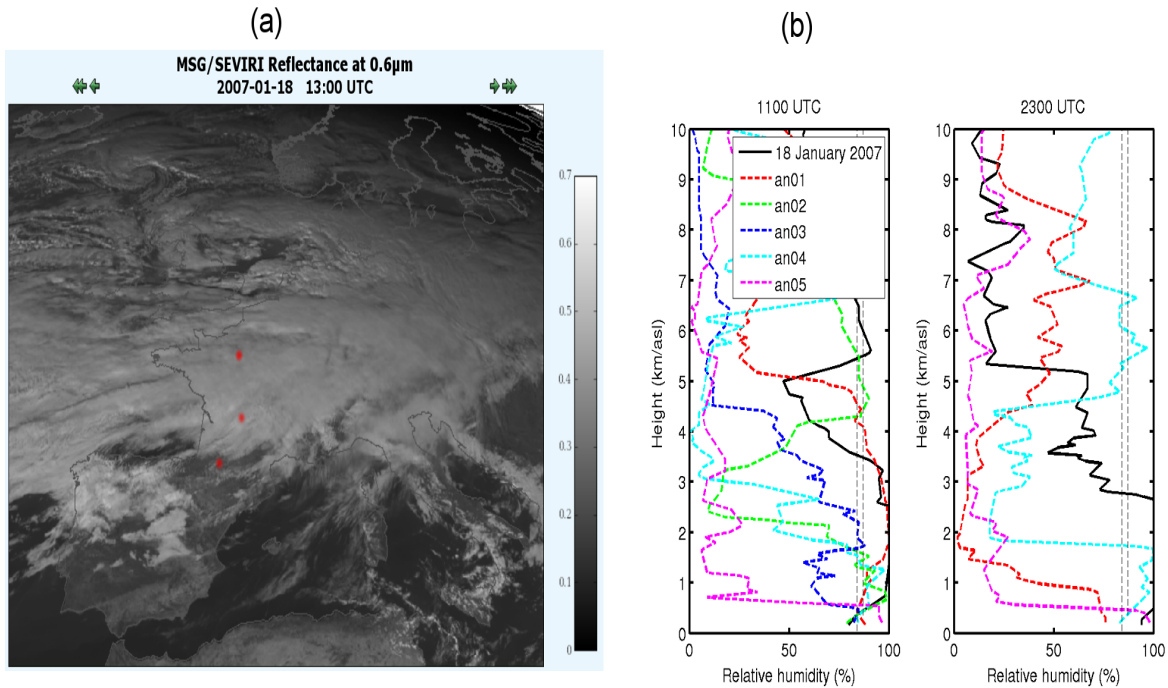
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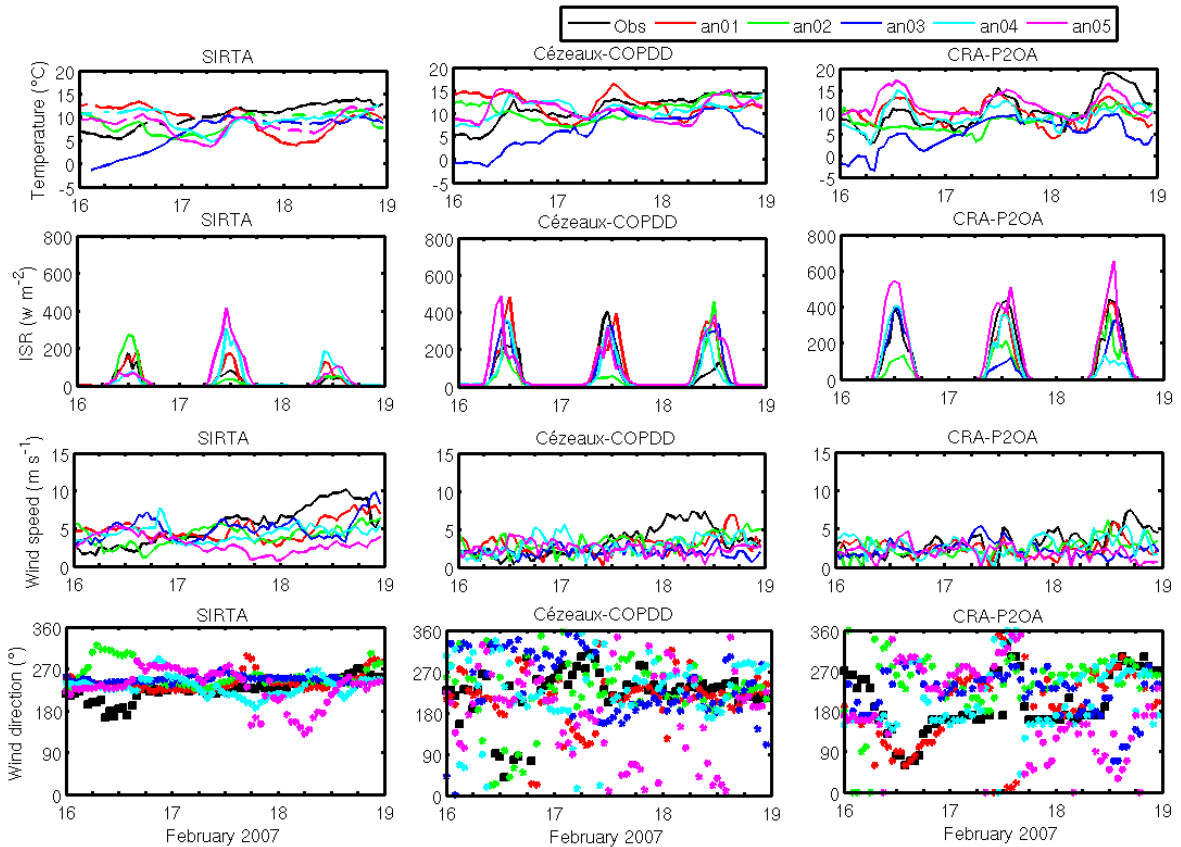
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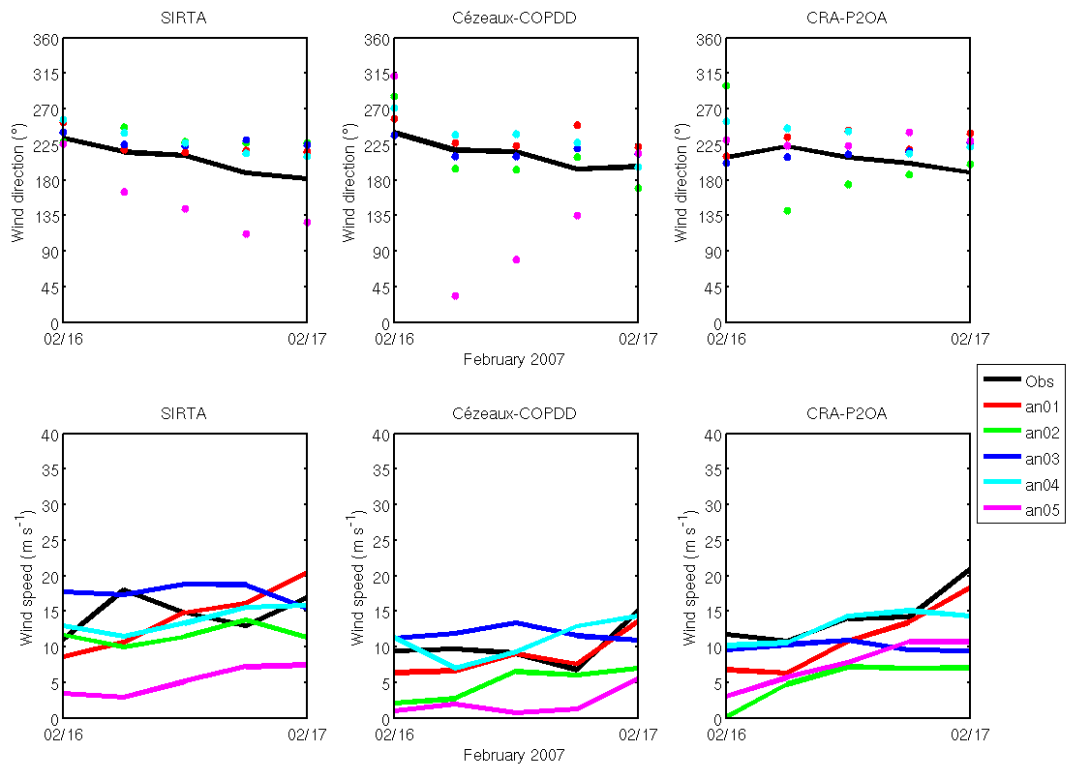
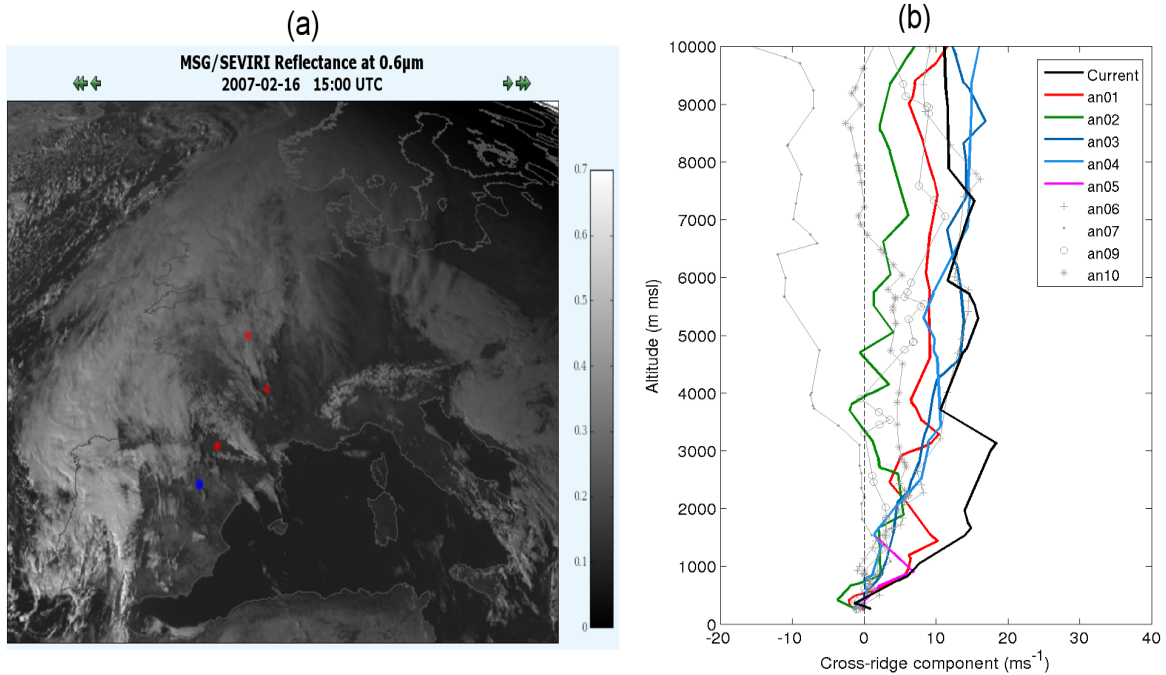


FIG. 11. As in Fig. 8 but for 16 February.



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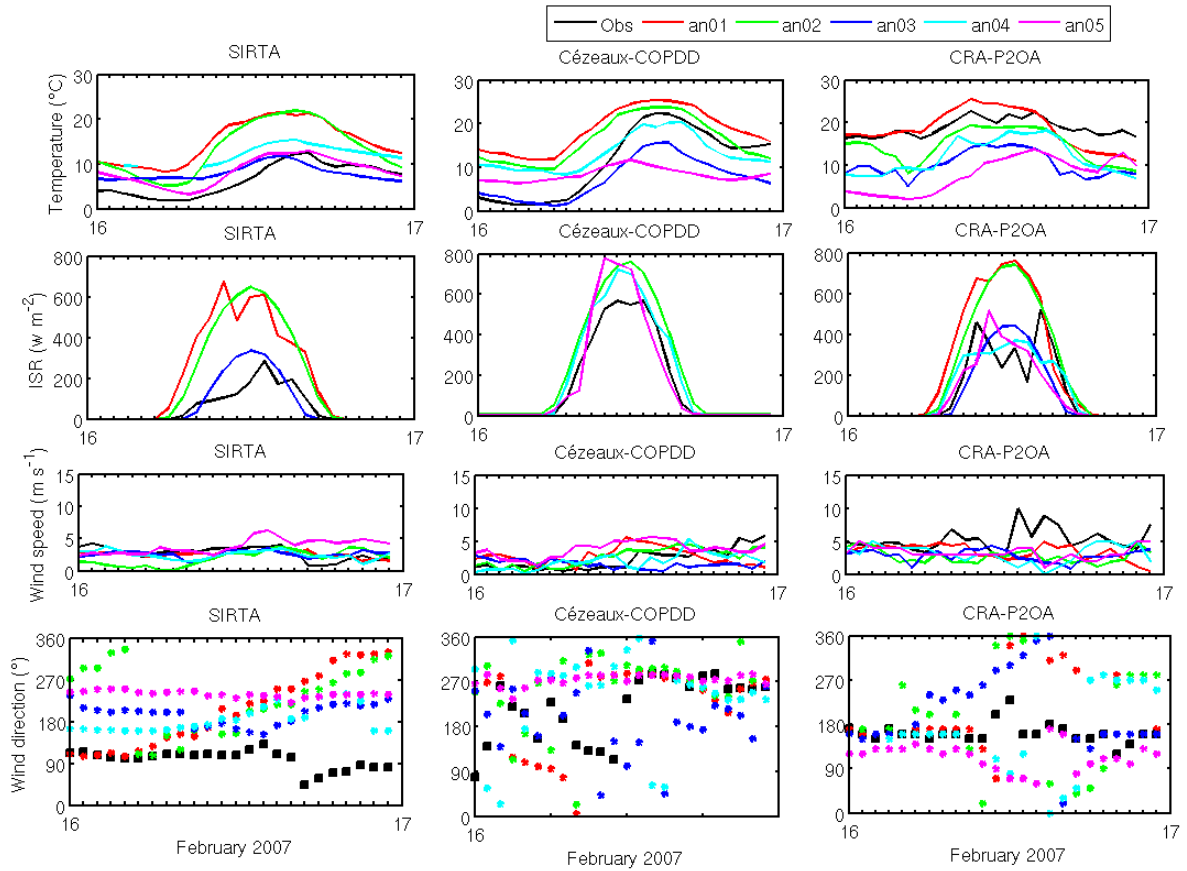


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