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1 Revisiting dynamic and thermodynamic processes
2 driving the January 2014 precipitation record in
3 southern UK

4 Boutheina Oueslati¹, Pascal Yiou¹, and Aglaé Jézéquel¹

5 ¹*Laboratoire des Sciences du Climat et de l'Environnement, UMR CEA-CNRS-UVSQ,*
6 *IPSL and U Paris-Saclay, 91191 Gif-sur-Yvette Cedex, France*

7 Many attribution studies of extreme events have attempted to es-
8 timate the thermodynamic contribution (linked to thermal changes)
9 and the dynamic contribution (linked to the atmospheric circulation).
10 Those studies are based on statistical decompositions of atmospheric
11 fields, and essentially focus on the horizontal motion of the atmosphere.
12 This paper proposes a framework that decomposes those terms from
13 first physical principles, which include the vertical atmospheric motion
14 that has often been overlooked. The goal is to take into account the
15 driving processes of the extreme event. We revisit a recent example
16 of extreme precipitation that was extensively investigated through its
17 relation with the atmospheric circulation. We find that although the
18 horizontal motion plays a minor (but important) role, the vertical mo-
19 tion yields a dominating contribution to the event that is larger than
20 the thermodynamic contribution. This analysis quantifies the processes
21 leading to high winter precipitation rates, and can be extended for fur-
22 ther attribution studies.

23

24 During the 2013/14 winter, southern UK has been affected by a spate of win-
25 ter storms associated with a strengthening of the North Atlantic jet stream [1].
26 This exceptional situation resulted in heavy precipitation, with a precipitation
27 record in southern UK (Fig.1a) [1, 2] and north western France in January. Such
28 extreme events are projected to intensify in this region as a response to planetary
29 climate change [3, 4], with important impacts on societies. Understanding the
30 driving processes of those events and their sensitivity to anthropogenic warming
31 is, therefore, crucial to anticipate the future risks of flooding over the UK.

32

33 A fruitful approach in climate event attribution consists in separating dy-
34 namic and thermodynamic contributions [5, 6, 7]. The thermodynamic processes
35 are associated with the enhancement of the atmospheric water vapor content,
36 following the Clausius-Clapeyron equation [8, 9, 10]. They are robust across cli-
37 mate models and result in a spatially homogeneous increase of precipitation [11].
38 The dynamic processes are related to the atmospheric circulation and remain
39 highly uncertain at the regional scale [12, 13, 14, 11]. They considerably influ-
40 ence the ClausiusClapeyron scaling, strengthening for example, the daily heaviest
41 precipitation [12, 13, 15, 14] and hourly precipitation extremes [16]. Therefore,

42 considering the driving mechanisms separately is useful to deal with the highly
43 uncertain dynamic changes and the robust thermodynamic changes in response
44 to anthropogenic forcings.

45

46 Several studies attempted to quantify those individual contributions during
47 the January 2014 heavy precipitation event. Schaller et al. [2] and Vautard et
48 al. [17] concluded that a third of the increase in January precipitation can be
49 attributed to changes in atmospheric dynamics and two thirds of the increase to
50 thermodynamic changes. The two studies differ by the metric used to measure
51 the effect of the circulation. Schaller et al. [2] used the daily mean sea-level
52 pressure (SLP) at a specific point as a proxy of the circulation. This metric is
53 a poor description of the atmospheric dynamics and accounts for only one local
54 feature of the flow. Vautard et al. [17] applied a more general method based
55 on flow analogues that are computed from monthly mean SLP over a regional
56 domain (eastern north Atlantic ocean and Europe). However, this approach is
57 sensitive to the way the similarity of the flows is approximated, either through
58 weather regimes or flow analogues [17, 18]. In addition, flows are characterized
59 by mean SLP patterns that only describe the low-level atmospheric circulation.
60 Such characterization misses the developing vertical circulation that controls the
61 initiation and strength of convection. Therefore the statistical approaches that
62 have been used might provide a partial view of the atmospheric circulation and
63 estimate only a part of the dynamic contribution to extreme events. In particular,
64 an explicit representation of the atmospheric velocity in the available statistical
65 diagnostics has been missing.

66

67 In this study, we propose an alternative framework to disentangle the dy-
68 namic and thermodynamic contributions. Changes in extreme precipitation are
69 decomposed using a robust physical approach based on the atmospheric water
70 budget (see Methods). This framework has been widely used in the tropics to
71 relate local changes in precipitation to changes in atmospheric water vapor and
72 circulation [e.g. 15, 19, 20]. This method is applied to January 2014 precipita-
73 tion to understand the physical drivers of this extreme event. It also provides
74 a physically-based quantification of dynamic and thermodynamic contributions
75 that might be useful for extreme event attribution. The analysis is carried out
76 using the ERA-Interim (ERA-I) reanalysis [21], motivated by the horizontal reso-

77 lution of this dataset (0.75°). The robustness of the results are tested using the
78 NCEP reanalysis [22] (Supplementary Material).

79

80 The monthly-mean pattern of precipitation anomaly during January 2014 is
81 better represented by ERAI (Fig.1b), as well as the daily variability. Both reanal-
82 yses, however, underestimate precipitation intensity. The monthly-mean water
83 budget is computed to relate January 2014 precipitation anomalies to changes
84 in the vertical moisture advection (ΔV_{adv}), the horizontal moisture advection
85 (ΔH_{adv}) and surface evaporation (ΔE) (Methods section and Fig.1c,d,e).

86

87 January 2014 precipitation in southern UK is characterized by stronger than
88 usual moisture vertical advection anomalies (larger than 2 mm/day on average for
89 ERAI and NCEP) (Fig.1c,f and Supplementary Fig.1a). These positive anoma-
90 lies moisten the troposphere by the vertical transport of moisture and sustain
91 low-level moisture convergence. Abundant moisture in the atmospheric column
92 and strong vertical motions resulted in heavy precipitation in southern UK. Hor-
93 izontal moisture advection is small and negative at monthly time scale. There-
94 fore it contributes to drying the troposphere and reducing precipitation intensity
95 (Fig.1d,g). Surface evaporation is small over land and in particular, over south-
96 ern UK (Fig.1e,f). Overall, January 2014 precipitation is dominated by moisture
97 convergence associated with vertical motion. The dominance of this physical
98 mechanism in inducing heavy precipitation has already been highlighted in pre-
99 vious studies [12, 13, 15, 11] using climate models.

100

101 At daily time-scale, vertical moisture advection is still the dominant process
102 in generating intense precipitation (Fig. 2a), with a positive correlation of 0.8
103 between daily-mean P and V_{adv} in January 2014. Vertical advection moistens the
104 troposphere through the vertical transport of moisture and is conducive to the
105 development of convection at the same day of maximum vertical advection. This
106 is the case for the heaviest rainy days of January 2014 (i.e. Jan. 1st, 4th, 18th,
107 24th and 31st), during which a minimum of 6 mm/day of V_{adv} was needed to
108 induce precipitation rates ranging between 6 to 13 mm/day. In contrast to the
109 vertical moisture advection, horizontal moisture advection has, in most cases, an
110 asymmetric temporal structure relative to the heavy precipitation events. Posi-
111 tive moisture advection peaks 1 day before the maximum rainfall and becomes

112 negative after the rainfall maximum (e.g. Jan. 24th). Thus it contributes to the
113 moistening of the troposphere before the maximum precipitation and to its drying
114 during the heavy rainfall events.

115

116 Our analysis decomposes the sequence of events that led to a high cumulated
117 precipitation. The horizontal advection H_{adv} is a necessary precursor and the ver-
118 tical advection V_{adv} is necessary and sufficient once enough moisture is available.

119

120 To identify the origin of the low-level moistening through horizontal moisture
121 advection, monthly-mean 850hPa winds and the vertically-integrated moisture
122 flux convergence are examined (Fig. 2b). Moisture convergence occurs over rainy
123 regions, particularly over southern UK. Moisture divergence is localized over the
124 North Atlantic, suggesting that this oceanic region is the primary source of mois-
125 ture for the UK. Westerly winds over the North Atlantic were much stronger than
126 normal during January 2014, favored by a persistent zonal circulation [2]. These
127 winds contributed to advect moisture eastward towards the UK causing heavy
128 precipitation and flooding. Moisture might also have been transported from the
129 subtropical North Atlantic by south-easterly winds. January 2014 could therefore
130 be connected to *atmospheric rivers*, which transport large flux of moisture from
131 the subtropics to the mid-latitudes, leading to heavy precipitation and flooding
132 over UK [23]. Back trajectory analyses are however needed to confirm the tropical
133 origin of moisture during this event.

134

135 To further understand the mechanisms inducing heavy precipitation in south-
136 ern UK, we focus on the dominant driver, i.e. the vertical moisture advection.
137 V_{adv} anomalies are divided into thermodynamic and dynamic contributions (Meth-
138 ods section, Fig.3 and Supplementary Fig.1b). The thermodynamic component
139 (*Thermo*) is associated with changes in water vapor that are largely dominated
140 by the Clausius Clapeyron relation [8, 9]. The dynamic component (*Dyn*) is asso-
141 ciated with changes in vertical velocity. *Dyn* and *Thermo* compute the vertically-
142 integrated dynamic and thermodynamic changes and include, therefore, the influ-
143 ence of temperature lapse-rates changes [24]. *Dyn* is the main contributor to the
144 vertical transport of moisture and contributes to more than 90% of V_{adv} anom-
145 alies over southern UK (Fig.3a,c). *Thermo* is very small (less than 1 mm/day in
146 southern UK) and contributes only little to V_{adv} anomalies (Fig.3b,c).

148 In conclusion, the atmospheric circulation was a crucial element for Jan-
149 uary 2014 heavy precipitation. This extreme event was dynamically-induced by
150 stronger vertical motions, which moistened the atmospheric column and promoted
151 convection. Evaluating how anthropogenic climate change may alter the dynamic
152 and thermodynamic contributions is essential to assess future projections of ex-
153 treme precipitation. The *Dyn* and *Thermo* components are relevant metrics in
154 that context. They yield a precise physical meaning at all vertical levels and at
155 a regional scale. These metrics can be used in extreme event attribution studies
156 (e.g. [2, 17, 18]) to provide a robust quantification of the role of the atmospheric
157 circulation and water vapor in future changes in extreme precipitation. This ap-
158 proach can be applied consistently to reanalysis data or model simulations to
159 analyze other wet winters. Our results do not necessarily contradict the existing
160 event attribution papers: we find that the dominant factor for high precipitation
161 is the vertical motion of the atmosphere. But long term changes in this advection
162 mechanism can be very small, compared to changes in the thermodynamic term
163 in the extra-tropics. They can even be of opposite sign [11]. Evaluating those
164 changes in a precise way is needed to gain confidence on the physical drivers of
165 precipitation extremes. This can be done with our Eq. (3), from long model
166 simulations or reanalyses. Those results follow the so-called storyline approach
167 advocated by Shepherd [7]. This helps constraining potential changes of those
168 components if a baseline climatology is altered to estimate the components of low
169 probability events.

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243 **Methods**

244 *Moisture budget*

245 Starting from the vertically-integrated water budget, regional precipitation at
246 daily time-scale can be decomposed as:

$$\begin{aligned} P &= E - \left[\omega \cdot \frac{\partial q}{\partial p} \right] - [\mathbf{V} \cdot \nabla q] - \left[\frac{\partial q}{\partial t} \right] \\ &= E + V_{adv} + H_{adv} - dq. \end{aligned} \quad (1)$$

247 where E is evaporation, ω the vertical profile of vertical velocity, \mathbf{V} the horizon-
248 tal wind and q the vertical profile of specific humidity. Brackets refer to mass-
249 weighted vertical integral. V_{adv} , H_{adv} and dq represent respectively the vertical
250 moisture advection, the horizontal moisture advection and the time derivative of
251 q .

252 The change in monthly-mean precipitation can be expressed as:

$$\Delta P = \Delta E + \Delta V_{adv} + \Delta H_{adv}. \quad (2)$$

253 *Dynamic and thermodynamic contributions to precipitation changes*

254 The vertical moisture advection is decomposed into a dynamic component (*Dyn*)
255 related to vertical velocity changes and a thermodynamic component (*Thermo*)
256 related to atmospheric water vapor changes that is largely dominated by Clausius
257 Clapeyron equation:

$$\Delta V_{adv} = - \left[\Delta \omega \cdot \overline{\frac{\partial q}{\partial p}} \right] - \left[\overline{\omega} \cdot \Delta \frac{\partial q}{\partial p} \right] = Dyn + Thermo, \quad (3)$$

258 where the overbar indicates the 1981–2010 climatology mean.

259

260 *Data availability*

261 Era-interim data are available from the ECMWF Public datasets web interface
262 (<http://apps.ecmwf.int/datasets>). NCEP data are available from the NOAA Pub-
263 lic datasets web interface (<http://www.esrl.noaa.gov/psd/thredds/dodsC/Datasets>).

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266 **Author contributions**

267 B.O. designed the study, performed the analysis, produced the figures and wrote
268 the paper. P.Y. provided advice in the study design and the interpretation of the
269 results and contributed to the writing. A.J. discussed the results and edited the
270 manuscript.

271 **Additional Information**

272 Competing Interests: The authors declare that they have no competing interests.

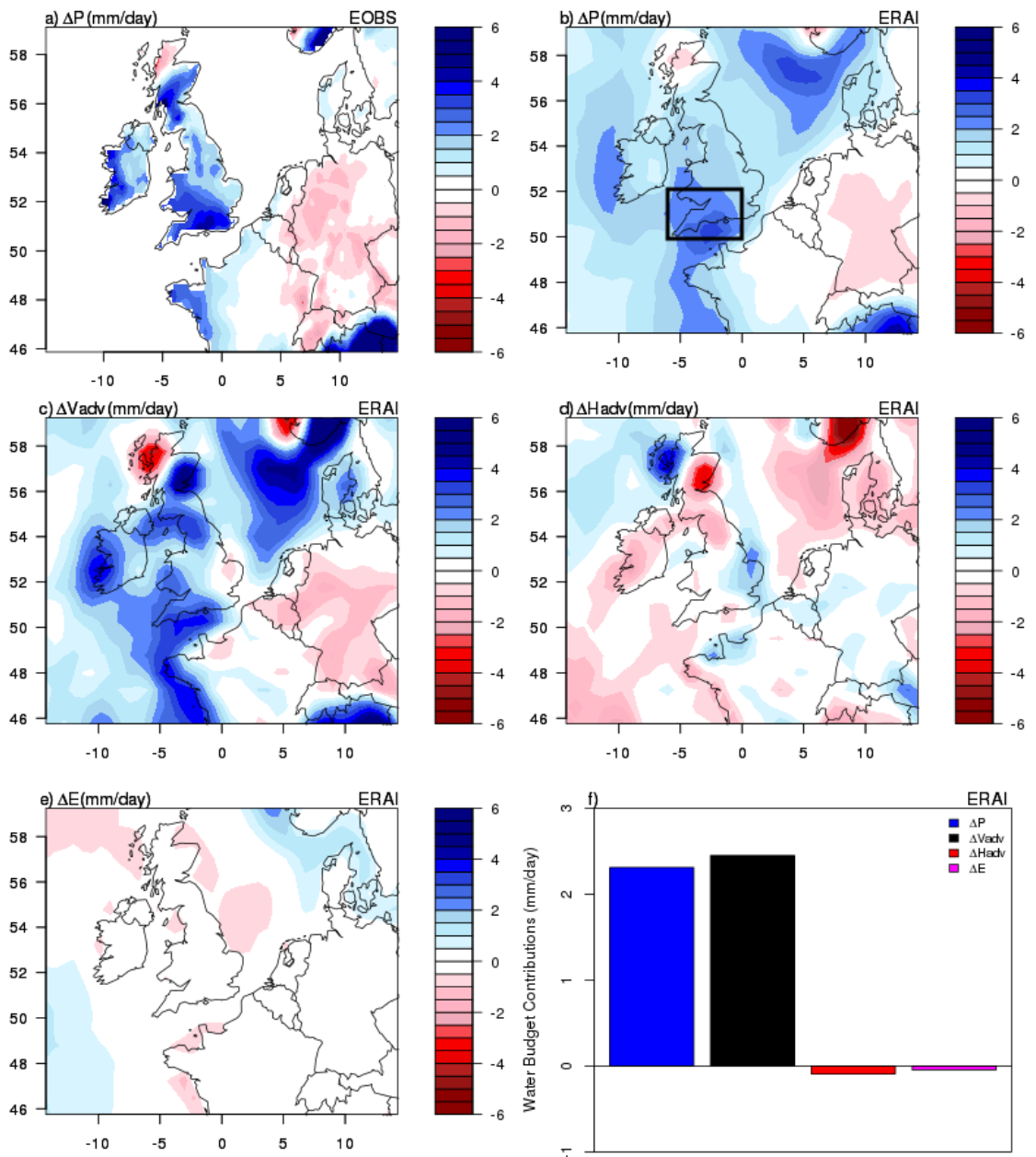


Figure 1: Monthly-mean anomalies for January 2014 of (a) EOBS [25] precipitation, (b) ERA-I precipitation, (c) Vertical moisture advection, (d) Horizontal moisture advection, (e) Surface evaporation, (f) the four water budget contributions averaged over southern UK ($50\text{-}52^\circ\text{ N}, 6.5^\circ\text{ W}\text{-}0^\circ$) as indicated by the black rectangle computed using ERA-I. Anomalies are relative to 1981-2010 climatology.

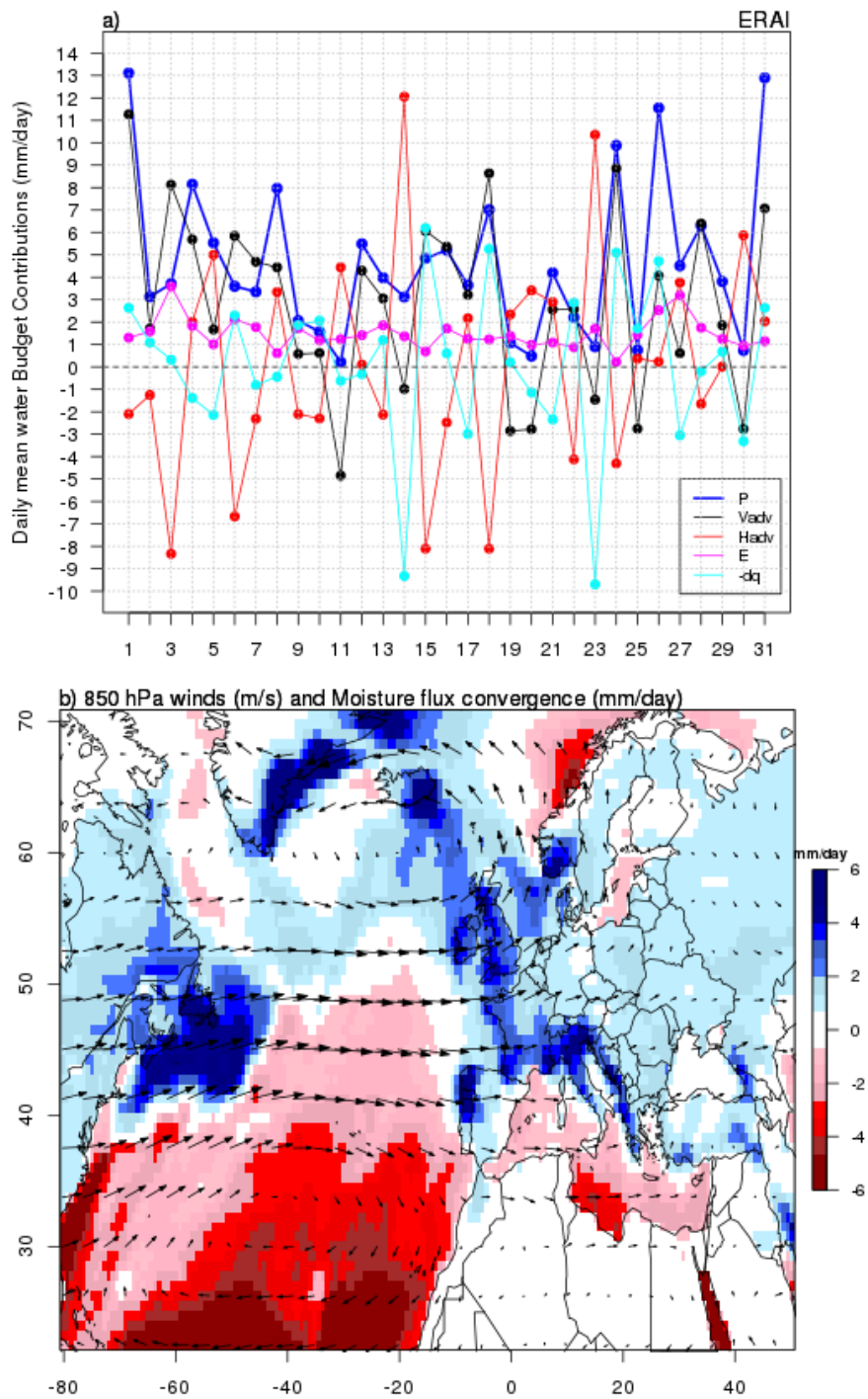


Figure 2: (a) Daily mean atmospheric water budget contributions for January 2014 averaged over southern UK, (b) Monthly-mean 850hPa horizontal winds and vertically-integrated moisture flux convergence for January 2014. Positive (negative) values correspond to areas of moisture flux divergence (convergence).

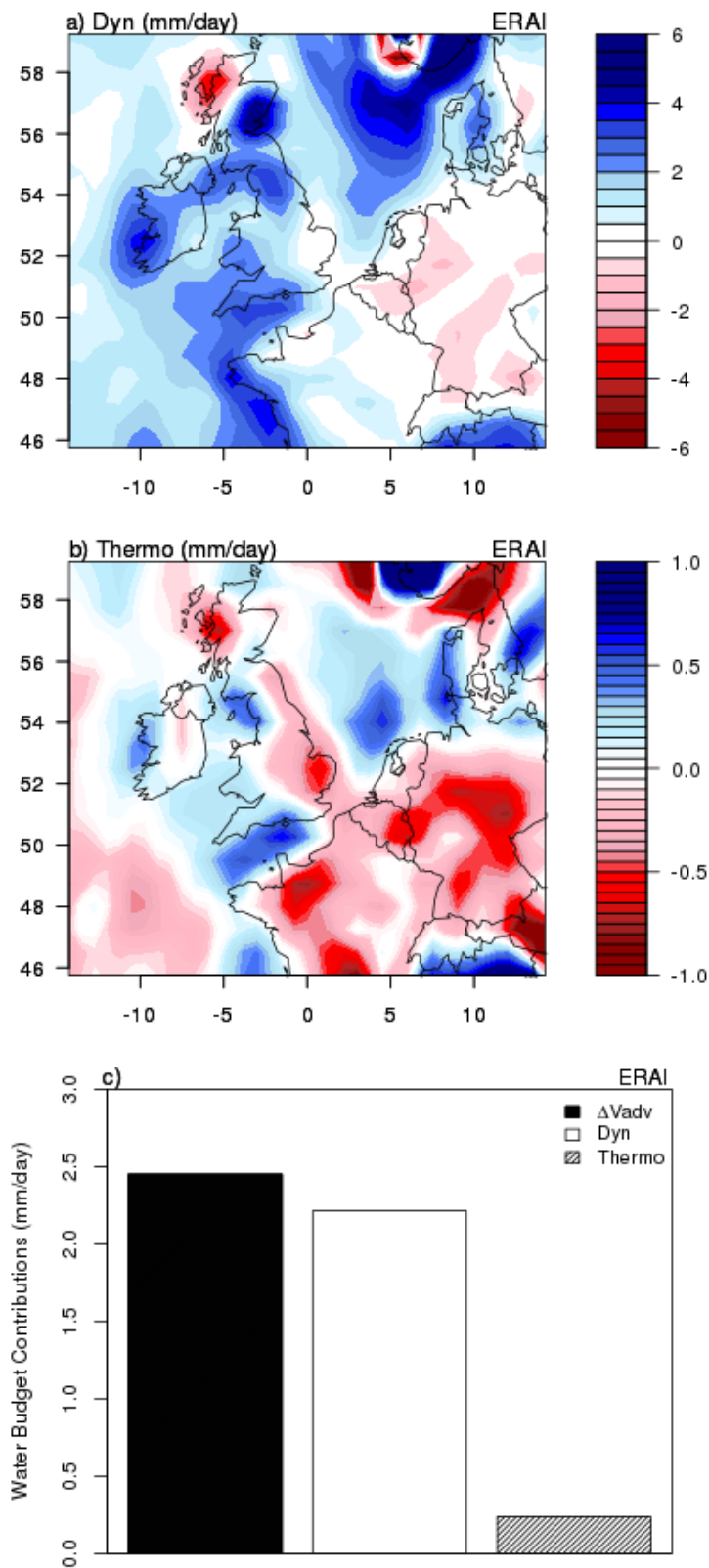


Figure 3: Monthly-mean anomalies of (a) dynamic and (b) thermodynamic contributions to precipitation anomaly during January 2014 derived from Eq. (3) using ERA-I, (c) As a, b but averaged over southern UK. Anomalies are relative to 1981-2010 climatology.