



# Revisiting dynamic and thermodynamic processes driving the January 2014 precipitation record in southern UK

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

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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 Clausius-Clapeyron 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-

lution of this dataset ( $0.75^\circ$ ). The robustness of the results are tested using the NCEP reanalysis [22] (Supplementary Material).

79

The monthly-mean pattern of precipitation anomaly during January 2014 is better represented by ERAI (Fig.1b), as well as the daily variability. Both reanalyses, however, underestimate precipitation intensity. The monthly-mean water budget is computed to relate January 2014 precipitation anomalies to changes in the vertical moisture advection ( $\Delta V_{adv}$ ), the horizontal moisture advection ( $\Delta H_{adv}$ ) and surface evaporation ( $\Delta E$ ) (Methods section and Fig.1c,d,e).

86

January 2014 precipitation in southern UK is characterized by stronger than usual moisture vertical advection anomalies (larger than 2 mm/day on average for ERAI and NCEP) (Fig.1c,f and Supplementary Fig.1a). These positive anomalies moisten the troposphere by the vertical transport of moisture and sustain low-level moisture convergence. Abundant moisture in the atmospheric column and strong vertical motions resulted in heavy precipitation in southern UK. Horizontal moisture advection is small and negative at monthly time scale. Therefore it contributes to drying the troposphere and reducing precipitation intensity (Fig.1d,g). Surface evaporation is small over land and in particular, over southern UK (Fig.1e,f). Overall, January 2014 precipitation is dominated by moisture convergence associated with vertical motion. The dominance of this physical mechanism in inducing heavy precipitation has already been highlighted in previous studies [12, 13, 15, 11] using climate models.

100

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

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

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

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

To further understand the mechanisms inducing heavy precipitation in southern UK, we focus on the dominant driver, i.e. the vertical moisture advection.  $V_{adv}$  anomalies are divided into thermodynamic and dynamic contributions (Methods section, Fig.3 and Supplementary Fig.1b). The thermodynamic component (*Thermo*) is associated with changes in water vapor that are largely dominated by the Clausius Clapeyron relation [8, 9]. The dynamic component (*Dyn*) is associated with changes in vertical velocity. *Dyn* and *Thermo* compute the vertically-integrated dynamic and thermodynamic changes and include, therefore, the influence of temperature lapse-rates changes [24]. *Dyn* is the main contributor to the vertical transport of moisture and contributes to more than 90% of  $V_{adv}$  anomalies over southern UK (Fig.3a,c). *Thermo* is very small (less than 1 mm/day in 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,  $\omega$  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 *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.

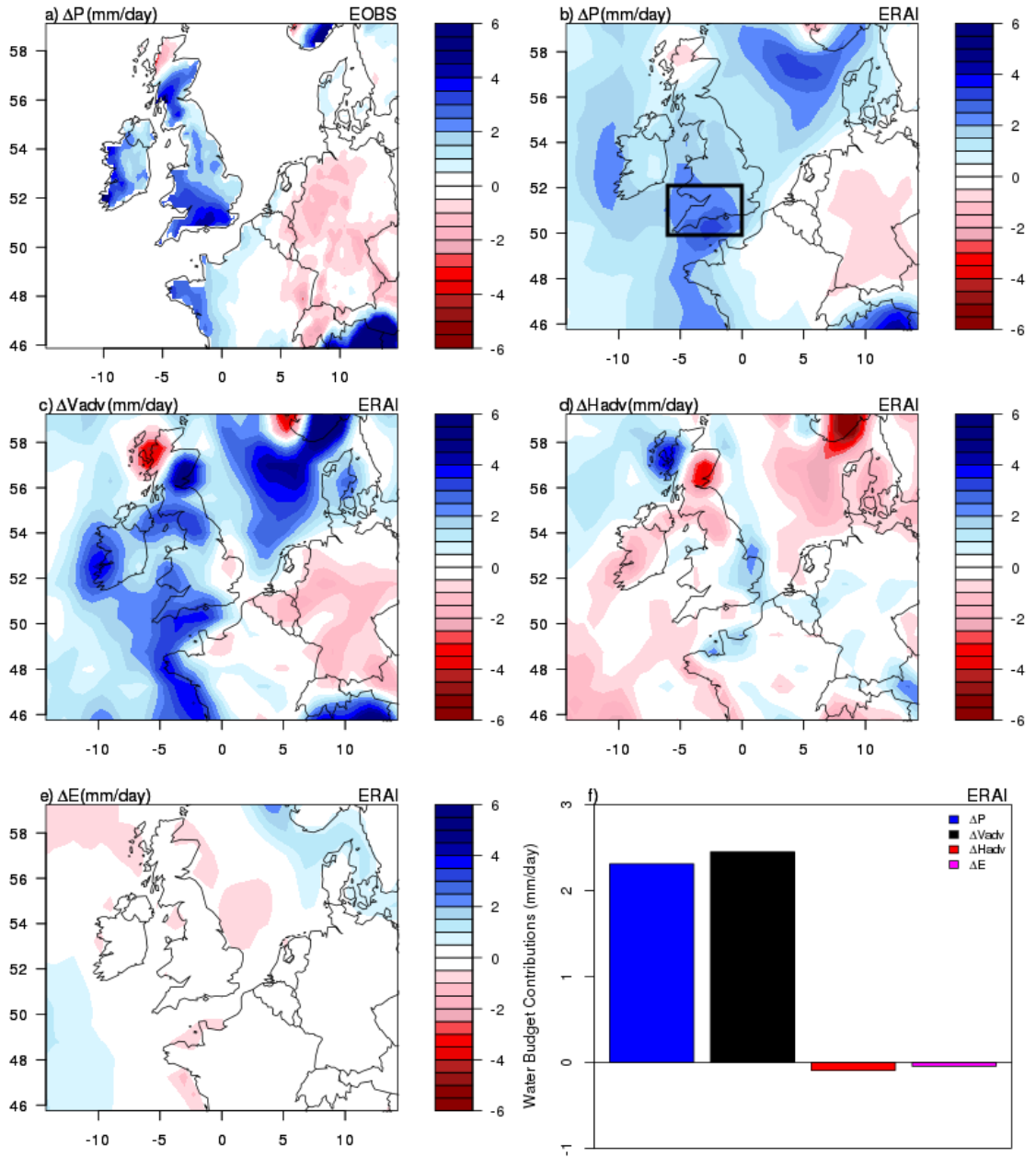


Figure 1: Monthly-mean anomalies for January 2014 of (a) EOBS [25] precipitation, (b) ERA-I precipitation, (c) Vertical moisture advection, (d) Horizontal moisture advection, (e) Surface evaporation, (f) the four water budget contributions averaged over southern UK (50-52° N, 6.5° W-0° ) as indicated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

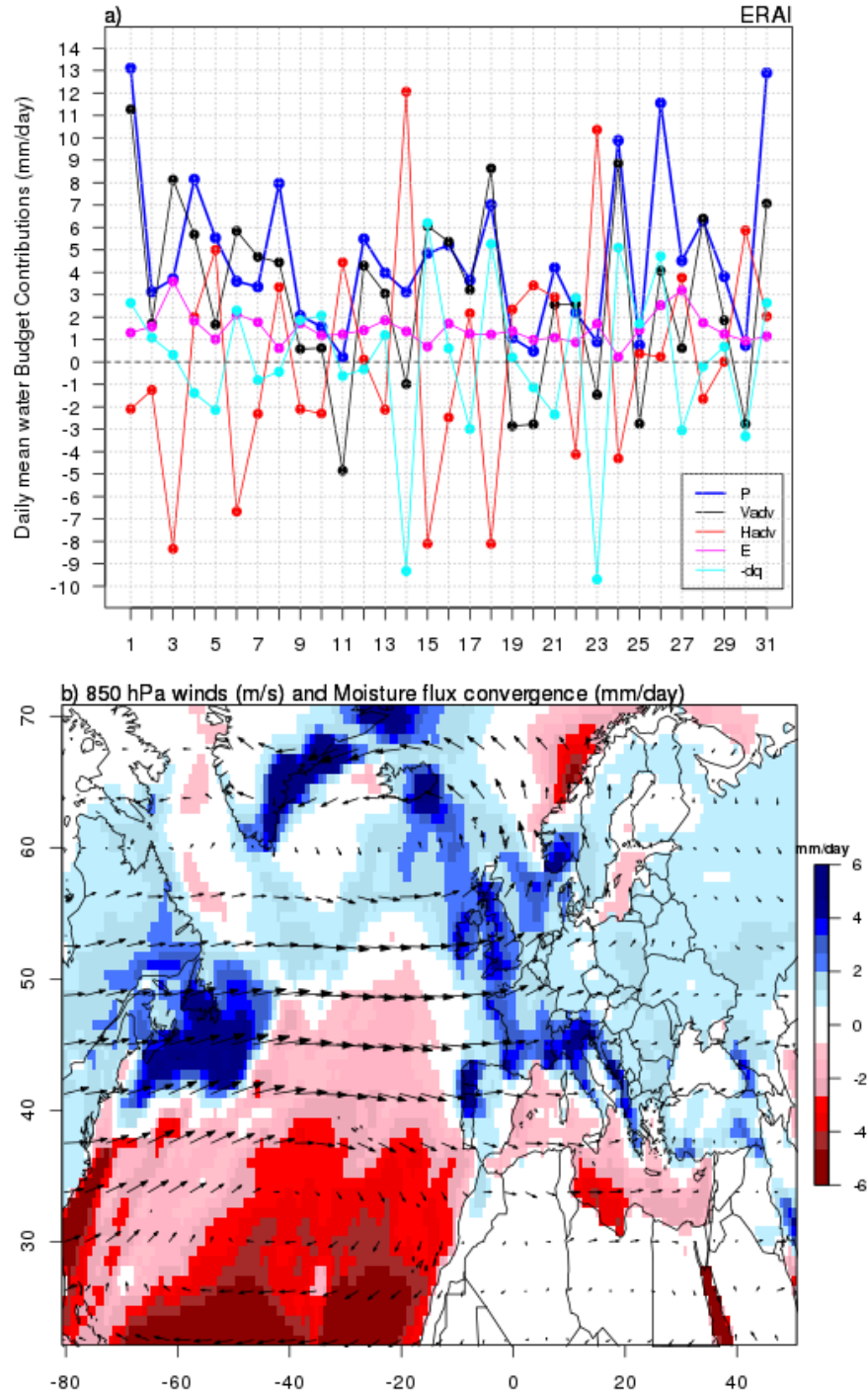


Figure 2: (a) Daily mean atmospheric water budget contributions for January 2014 averaged over southern UK, (b) Monthly-mean 850hPa horizontal winds and vertically-integrated moisture flux convergence for January 2014. Positive (negative) values correspond to areas of moisture flux divergence (convergence).

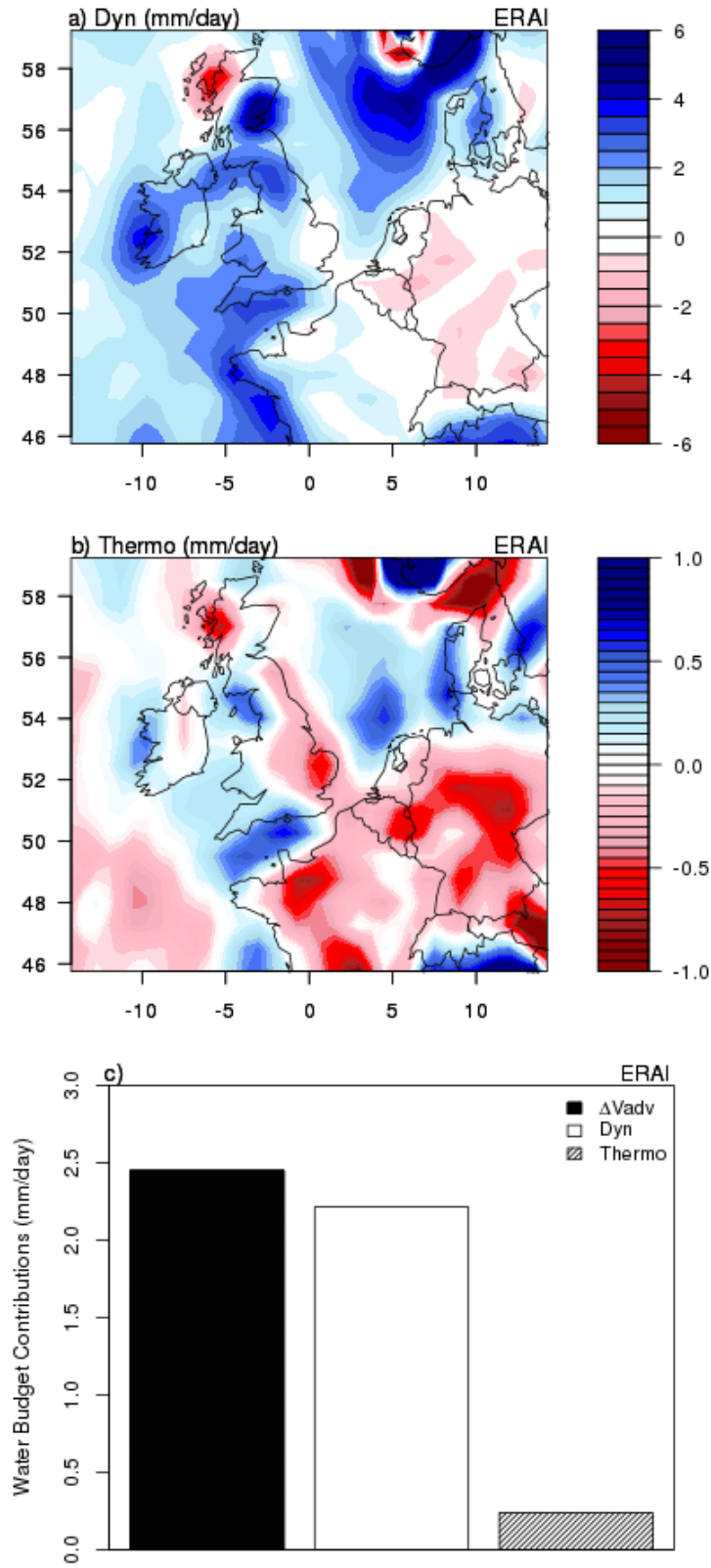


Figure 3: Monthly-mean anomalies of (a) dynamic and (b) thermodynamic contributions to precipitation anomaly during January 2014 derived from Eq. (3) using ERA-I, (c) As a, b but averaged over southern UK. Anomalies are relative to 1981-2010 climatology.