Narrative Review

PAIN

OPEN

Are weather conditions associated with chronic musculoskeletal pain? Review of results and methodologies

Anna L. Beukenhorst[a,*], David M. Schultz[b,c], John McBeth[a,d], Jamie C. Sergeant[a,e], William G. Dixon[a,d]

Abstract

Many people believe that weather influences chronic musculoskeletal pain. Previous studies on this association are narratively reviewed, with particular focus on comparing methodologies and summarising study findings in light of study quality. We searched 5 databases (Medline, Embase, Web of Science, PsycINFO, and Scopus) for observational studies on the association between weather variables and self-reported musculoskeletal pain severity. Of 4707 located articles, 43 were eligible for inclusion. The majority (67%) found some association between pain and a weather variable. Temperature, atmospheric pressure, relative humidity, and precipitation were most often investigated. For each weather variable, some studies found an association with pain (in either direction), and others did not. Most studies (86%) had a longitudinal study design, usually collecting outcome data for less than a month, from fewer than 100 participants. Most studies blinded participants to study aims but were at a high risk of misclassification of exposure and did not meet reporting requirements. Pain severity was most often self-reported (84%) on a numeric rating scale or visual analog scale. Weather data were collected from local weather stations, usually on the assumption that participants stayed in their home city. Analysis methods, preparation of weather data, and adjustment for covariates varied widely between studies. The association between weather and pain has been difficult to characterise. To obtain more clarity, future studies should address 3 main limitations of the previous literature: small sample sizes and short study durations, misclassification of exposure, and approach to statistical analysis (specifically, multiple comparisons and adjusting for covariates).

Keywords: Pain, Musculoskeletal diseases, Weather, Statistical methods, Observational studies, Study design

1. Introduction

"Doctor, can you give me a prescription to move to Spain?" Rheumatic patients in colder midlatitude climates have received arthritis treatment in subtropical climates for centuries.[8,30,43] Between 62% and 97% of people with musculoskeletal conditions believe that the weather influences their pain.[31,58,70]

Sponsorships or competing interests that may be relevant to content are disclosed at the end of this article.

[a] Centre for Epidemiology Versus Arthritis, Manchester Academic Health Science Centre, University of Manchester, Manchester, United Kingdom, [b] Centre for Atmospheric Science, School of Earth and Environmental Sciences, University of Manchester, Manchester, United Kingdom, [c] Centre for Crisis Studies and Mitigation, University of Manchester, Manchester, United Kingdom, [d] NIHR Greater Manchester Biomedical Research Centre, Manchester Academic Health Science Centre, University of Manchester, Manchester, United Kingdom, [e] Centre for Biostatistics, Manchester Academic Health Science Centre, University of Manchester, Manchester, United Kingdom

**Corresponding author. Address: Centre for Epidemiology Versus Arthritis, Stopford Building, Manchester M13 9PL, United Kingdom. Tel.: +44 (0)161 275 5044. E-mail address: anna.beuk@manchester.ac.uk (A.L. Beukenhorst).*

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.painjournalonline.com).

PAIN 161 (2020) 668–683

http://dx.doi.org/10.1097/j.pain.0000000000001776

Despite this belief among patients, there is no scientific consensus on the association between weather and musculoskeletal pain. Previous literature reviews on this topic have usually focused on research of 1[21,54,65] or 2[48] musculoskeletal conditions. Some reviews state that current evidence does not support an association between weather and pain,[39,65] whereas others show an association, although generally small and of debatable statistical and/or clinical significance.[21,46,48,54,62]

In previous reviews, aggregating study results was hampered by methodological heterogeneity.[48,54,65] For example, studies differed in choice of outcomes, exposures, and populations. Pain is subjective and individual, and researchers can focus on different aspects (eg, severity, changes, and flares). The weather can be described by many variables (eg, temperature, humidity, and pressure) that are not independent of each other. Both pain and weather change continuously but are usually measured at fixed intervals, the timing and frequency of which may differ. How these choices in individual studies are made has consequences for the study scope, design, and results. By reviewing studies on any musculoskeletal condition and considering their methodological heterogeneity, it may be possible to find patterns within studies using a similar approach and to move towards a clearer understanding of an otherwise confusing literature.

The aim of this review was to identify and synthesize studies of the association between weather variables and chronic pain in people living with musculoskeletal disease, with particular focus on the consequences of methodological choices (eg, definition of exposure and outcome, frequency and method of data collection, and statistical methods). This article is organized as follows. We first describe the literature search and the characteristics of identified published studies. Then, we summarize their findings. We highlight differences between these studies, between all studies investigating a specific weather variable (eg, temperature, pressure, and humidity), and between subpopulations (eg, per musculoskeletal disease). We then summarize and discuss the methodological heterogeneity, identifying differences in study design, collection of weather and pain data, data preparation and analysis, and risk of bias.

2. Methods

2.1. Search strategy

We searched Medline, Embase, Web of Science, Scopus, and PsycINFO from the earliest available date to January 31, 2017. The search strategy combined terms related to weather (eg, "*meteorol*," "weather") with terms related to chronic musculoskeletal pain (eg, "arthritis") and pain (eg, "pain"; see the Supplementary Material for the complete search strategy, available at http://links.lww.com/PAIN/A932). Where available, we used thesaurus headings and filters to limit the search to original research on humans.

Identified records were sequentially screened by AB according to the eligibility criteria: studies investigating weather conditions as exposure, in populations with musculoskeletal conditions, with pain as the outcome. Studies that were not in humans, not original research, not observational (ie, letters, conference abstracts, newspaper articles, and literature reviews), or in other languages than English were excluded. Articles were first screened for eligibility based on their title, and then, if needed, based on full text.

2.2. Data extraction and synthesis

To address the study objectives, AB extracted data from eligible articles and performed a quality assessment. Any uncertainties were discussed with coauthors. The quality assessment identified risks of bias due to misclassification of exposure (1. Was weather retrieved from participants' actual locations? 2. Was time spent outside measured?), adequacy of the length of follow-up (3. Was outcome data retrieved during 4 seasons?), lack of blinding of participants (4. Were participants blinded to study aims?), and reporting bias (5. Were all effect sizes reported? 6. Were uncertainty and/or exact *P* values reported?). For cross-sectional studies that by definition do not retrieve multiple outcomes per participant, item 3 was not applicable. For studies that estimated correlations between pain and single weather variables, we assessed adequacy of statistical methods with 2 additional assessment criteria (7. Did the analysis account for repeated measurements within participants? 8. Did authors correct for multiple testing?).

We then performed a narrative synthesis of this extracted data. We described study characteristics and synthesized study findings. We reported on how many studies found an association between weather and pain, and whether this was at population level (same association for all participants) or only in subgroups (different results for a subset of the participants). We reported on the results of the quality assessment and reflected on the studies' findings in the light of risk of bias, quality of reporting, and sample size. For each weather variable, we showed how many studies investigated that weather variable, how many studies found an association between pain and that weather variable, and how many did not. We then appraised methodological variability in choice of outcome, exposure and statistical method.

3. Results

The search of 5 databases returned 4707 articles, of which 493 were duplicates. The remaining 4214 records were screened according to the eligibility criteria, and 4106 records were excluded based on article titles. Full text of the remaining 108 articles was assessed for eligibility. Of these 108 articles, 65 were excluded because they did not investigate weather conditions, musculoskeletal conditions, or pain or because they were the wrong publication type, not observational studies, or not written in English (**Fig. 1**). In total, 43 articles were eligible to be included in the review.

3.1. Study design, disease population, sample size, and study duration

Of the 43 included articles, 37 (86%) were longitudinal studies, taking repeated measures of weather and pain through time. Of these, 32 were longitudinal cohort studies, following the same group of individuals through time. These studies can provide information on pain patterns over time and how weather patterns precede pain events. They enable analysis of both change within individuals and variation between individuals. The longitudinal cohort studies fell into 2 categories. The first category consisted of 13 studies that estimated correlations between pain and single weather variables, without adjusting for confounders. These studies were exploratory, and a first step towards quantifying associations between weather and pain. The second category consisted of 24 studies that assessed associations between pain and multiple predictors (multiple weather variables simultaneously and/or other covariates). These studies can more easily correct for confounding. Five of these 24 studies had a case-crossover design, where the weather during hazard periods (days with a pain exacerbation) was compared with the weather during control periods (similar days without pain exacerbation) within the same participant. Case-crossover studies use each participant as their own control, thus correcting by design for all time-invariant confounders, but they consider dichotomous rather than continuous pain outcomes and do not explicitly assess differences between individuals. The remaining 6 studies (6/43; 14%) were not longitudinal but cross-sectional, studying populations at one specific point in time. Cross-sectional studies estimate the associations between weather and pain at a snapshot in time using differences in exposures and outcomes between individuals but cannot address temporal changes in exposure or make within-person comparisons. A full table of study characteristics is presented in the Supplementary Material (available at http://links.lww.com/PAIN/A932).

Of the 43 studies, 34 (79%) investigated 1 musculoskeletal condition: rheumatoid arthritis (10/43; 23%;[1,11,15,25,26,38,53,58,61,66]), osteoarthritis (9/43; 21%;[9,12,20,22,45,50,56,71,77]), fibromyalgia or chronic widespread pain (8/43; 19%[6,7,18,23,31,49,64,74]), low-back pain (4/43; 9%;[4,16,51,68]), gout (2/43; 5%;[3,52]), or juvenile rheumatoid arthritis (1/43; 2%;[72]). The remaining 9 studies (9/43; 21%) investigated 2 or more of the following populations: people with rheumatoid arthritis or osteoarthritis,[2,10,29,41,63,69,73] fibromyalgia,[29,69] low-back pain,[44] spondyloarthritis,[10,41] "other arthritis,"[29] "other nontraumatic joint disorders,"[41] or complex regional pain syndrome and adhesive capsulitis of the shoulder.[44]

Most studies (36/43; 84%) investigated self-reported pain severity, including all 32 cohort studies, one case-crossover study[20] and 3 cross-sectional studies.[25,49,56] The other 7 studies (16%) used databases of existing health information to identify hospital visits for pain-related complaints including emergency visits for rheumatoid arthritis,[1] hospital admissions for rheumatoid

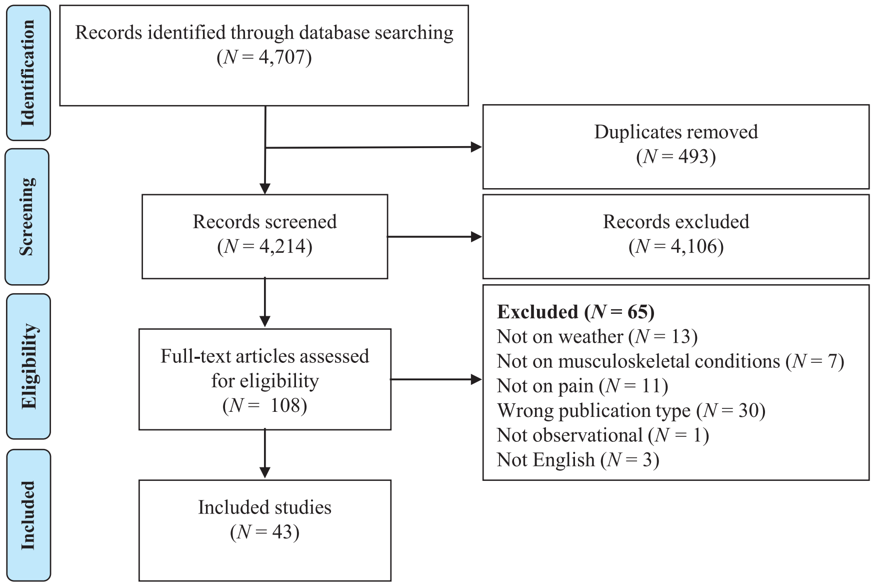

Figure 1. Flow diagram of screening and inclusion of relevant articles.

arthritis,[38] gout attacks,[3,52] low-back pain episodes,[4,68] and proportion of outpatient visits for joint/back pain.[41] Sources of these data were electronic medical records databases,[1,3,38,52,68] a drug-trial database,[4] and an insurance-claims database.[41]

Participant numbers in the 43 studies ranged from 18 to more than 1.5 million, and study durations ranged from 1 to 365 days (**Fig. 2**). The 37 longitudinal studies investigated 18 to 1604 participants (median 88) and collected outcome data for 2 to 365 days (median 29; not reported in Ref. 31). Most longitudinal studies (26/37; 70%) collected data on a series of consecutive days. Some studies (11/37; 29%) collected data intermittently, resulting in study durations longer than the "days of outcome data collection" displayed in **Figure 2**. For example, studies had intermittent data collection during periods of less than a year (14 days up to 6 months[6,22,45,50,66]) or 1 year or more[2,12,15,58,71,77] (See Supplementary material, available at http://links.lww.com/PAIN/A932). Four studies (4/35; 11%) reported individual differences in days of outcome data collection[11,15,59,74]; for these, the mean is displayed in **Figure 2** (eg, between 4 days and 5 weeks with a mean of 15.3 days). Three of the 5 case-crossover studies retrospectively identified hazard periods,[1,4,68] whereas the other 2 case-crossover studies identified hazard periods prospectively over periods of 90[20] and 365 days.[52] All 5 case-crossover studies matched each hazard period with 2 to 4 control periods, resulting in "days of outcome data collection" from 3 (2 control periods + 1 hazard period) to 5 (4 control periods + 1 hazard period) days in **Figure 2**. Of note, the case-crossover studies did not actively collect data on control periods (days without the dichotomous outcome) but assumed that the same day a week to a month before or after the hazard period was a control period. The 6 cross-sectional studies included one outcome data point for 82 to more than 1.5 million people (median 13,629).

3.2. Synthesis of study findings

Using the authors' interpretation of their own findings, the majority of the studies reported an association between weather and pain (27/43; 63%). Sometimes, studies with similar results had different interpretations, in particular, when associations of marginal statistical or clinical significance were found. For example, some studies concluded that weather and pain were associated but specified that this association was small. These studies describe their results as "not clinically important,"[64,68] making a "minimal contribution to pain"[12,15,25] or "very small,"[26,50] where "very small" referred to a 10°C increase in temperature being associated with a 0.6-unit decrease in pain on a 100-point scale.[26] Other studies concluded there was no association between weather and pain, despite finding at least one relationship between a weather variable and pain.[4,7,20] Thus, the 63% of studies that reported an association is affected by the authors' interpretation of their own findings.

Of the 29 studies that reported an association, 19 found a population-level effect and 10 found an effect in subgroup(s) only. Of these 10 studies, 5 stratified participants by specific characteristics such as disease,[10,69,73] geographical area and self-reported weather sensitivity,[45] or age group.[1] For example, subgroup effects were found in participants with spondyloarthritis and osteoarthritis, but not rheumatoid arthritis[10]; in participants from urban areas with self-reported weather sensitivity, but not in participants from urban areas without self-reported weather sensitivity or in participants from rural areas[45]; and in participants 50 to 65 years old, but not other age groups.[1] The other 5 studies that examined subgroups analyzed the data of each individual independently and reported significant associations in 16.6% to 92.9% of participants.[11,29,44,59,66]

When interpreting study results, it is useful to reflect on the scope and quality of the studies, which we will do in the 3 categories identified in Section 3.1: cross-sectional studies, longitudinal studies estimating correlations between pain and one predictor, and longitudinal studies assessing associations between pain and multiple predictors (multiple weather variables and/or other covariates).

The cross-sectional studies were scored on 5 quality criteria (**Table 1**). Of 6 cross-sectional studies, none met all quality criteria. Two met 3 quality criteria (2/6; 33%;[41,49]), 2 met 2 quality criteria (2/6; 33%;[25,38]), and 2 met one quality criterion (2/6; 33%;[3,56]). Of the 2 studies that met 3 quality criteria, one found an association between the weather and pain, and one did not find an association.

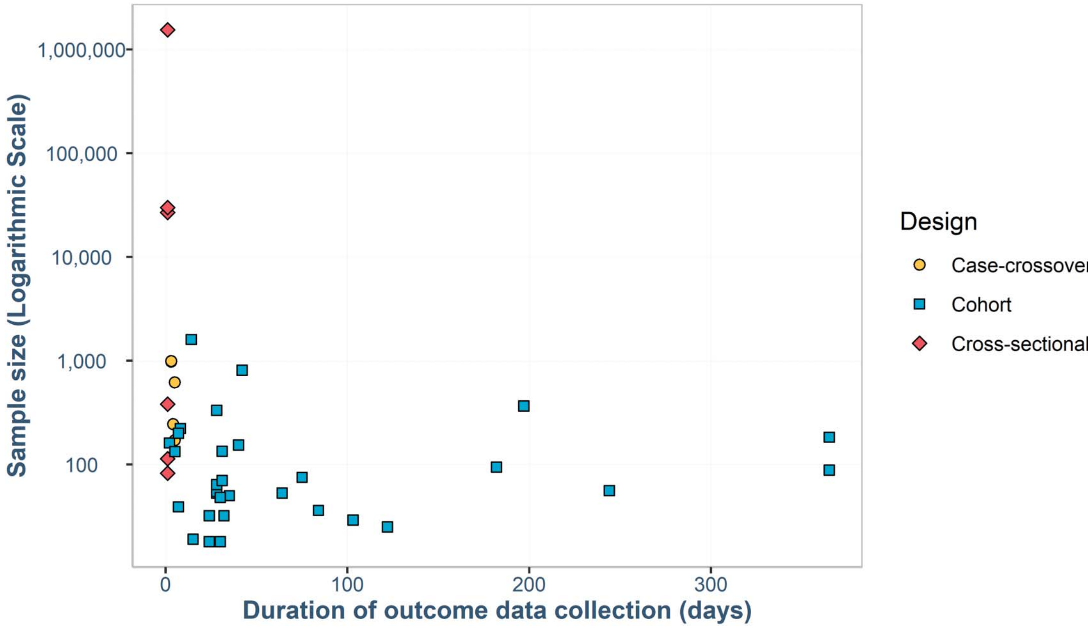

Figure 2. Sample size (on logarithmic axis) and duration of outcome data collection (days) of the 43 included studies. Shape and color denotes study design: yellow circles for case-crossover studies, blue squares for cohort studies, and red diamonds for cross-sectional studies.

Of note, the study that did not find an association only investigated rainfall.[41] All studies that met 1 or 2 quality criteria found an association between weather and pain.

The cross-sectional studies were at high risk of misclassification of exposure because only one study retrieved the weather from the participants' locations,[56] and none considered time spent outside. In 5 studies, participants were blinded to the study aims[3,25,38,41,49] (not reported in Ref. 56). The quality of reporting varied, with 4 studies reporting all effect sizes,[25,38,41,49] but only 2 studies reporting uncertainty.[41,49]

In total, 13 longitudinal studies calculated correlation coefficients between pain and single weather variables, without correcting for confounding. These studies were scored on 8 quality criteria (**Table 2**). One met 5 quality criteria and did not find an association between pain and either of 3 weather variables.[77] Two met 4 quality criteria and did not find an association between weather and pain either.[6,61] Three studies met 3 quality criteria.[11,53,69] All 3 found an association between weather and pain, one at population level for rheumatoid arthritis patients,[53] and one for 2 of 3 patient groups only (patients with fibromyalgia and osteoarthritis, but not with rheumatoid arthritis[69]). One calculated correlations for each of 6 weather variables and pain of each of 19 participants, resulting in significant correlations for 69% of participants.[11] Six studies met 2 quality criteria.[31,44,58,59,63,72] One found an association (although no hypothesis tests were performed[59]), one found an association

Table 1

Results, sample size, and quality assessment of cross-sectional studies.

	Study	Author-reported association	Sample size	No. of weather variables investigated	Weather from participant location	Time spent outside considered	Blinding to study aims	Reported all effect sizes	Reported uncertainty
Met 3 Quality Criteria	Jena et al.[47]	No	1,552,842	1	Not met	Not met	Met	Met	Met
	Macfarlane et al.[49]	Yes	381	4	Not met	Not met	Met	Met	Met
Met 2 Quality Criteria	Işik et al.[38]	Yes	29,996	6	Not met	Not met	Met	Met	Not met
	Glaser et al.[25]	Yes	26,877	7	Not met	Not met	Met	Met	Not met
Met 1 Quality Criterion	Peultier et al.[56]	Yes	113	6	Met	Not met	NR	Not met	Not met
	Arber et al.[3]	Yes	82	2	Not met	Not met	Met	Not met	Not met

Author-reported association: Did authors find a relation between weather and pain? Yes, if authors report at least one association between a weather variable and pain, otherwise No.
Quality assessment:
Weather from participant location: "Met" if weather was retrieved from participants' actual locations, otherwise "Not Met."
Time spent outside considered: "Met" if participants' time spent outside was measured, otherwise "Not Met."
Sufficient length of follow-up: "Met" if outcome data were retrieved during 4 seasons (covering the full range of weather variation), otherwise "Not Met."
Blinding to study aims: "Met" if participants were unaware of study aim/hypothesis, otherwise "Not Met."
Reported all effect sizes: "Met" if effect sizes were reported, both of significant and nonsignificant findings, otherwise "Not Met."
Reported uncertainty: "Met" if confidence intervals were reported, otherwise "Not Met."
NR, not reported.

Table 2

Results, sample size, and quality assessment of longitudinal cohort studies calculating correlation coefficients of pain and a single weather variable.

	Study	Author-reported association	Sample size	No. of weather variables investigated	Weather from participant location	Time spent outside considered	Sufficient length of follow-up	Blinding to study aims	Accounted for repeated measures	Corrected for multiple testing	Reported all results	Reported exact *P* values
Met 5 Quality Criteria	Wilder et al.[77]	No	154	3	Not met	Not met	Met	Met	Met	Met	Not met	Met
Met 4 Quality Criteria	Savage et al.[61]	No	133	6	Met	Not met	Not met	NR	Met	Not met	Met	Met
	De Blecourt et al.[6]	No	32	7	Not met	Not met	Not met	Met	Not met	Met	Met	Met
Met 3 Quality Criteria	Strusberg et al.[69]	Yes*	183	3	Not met	Not met	Met	Met	Not met	Met	Not met	Not met
	Patberg et al.[53]	Yes	88	5	Not met	Not met	Met	Met	Not met	Not met	Met	Not met
	Dequeker and Wuestenraed[11]	Yes*	19	6	Met	Met	Not met	Not met	Met	Not met	Not met	Not met
Met 2 Quality Criteria	Rentschler et al.[59]	Yes	367	3	Met	Not met	Met	NR	Not met	NA*	Not met	NA*
	Hagglund et al.[31]	No	84	4	Not met	Not met	NR	Met	Not met	Met	Not met	Not met
	Sibley[63]	No	70	5	Not met	Not met	Not met	Met	Not met	Not met	Met	Not met
	Tsai et al.[72]	No	29	5	Not met	Not met	Not met	Met	Not met	Not met	Met	Not met
	Koyama et al.[44]	Yes*	18	7	Not met	Not met	Not met	Met	Met	Not met	Not met	Not met
	Redelmeier and Tversky[58]	No	18	3	Not met	Not met	Met	NR	Met	Not met	Not met	Not met
Met 1 Quality Criterion	Viitanen et al.[74]	No	39	4	Not met	Not met	Not met	Met	Not met	NA*	Not met	NA*

Author-reported association: Did authors find a relation between weather and pain? Yes, if authors report at least one association between a weather variable and pain, Yes* if authors report an association in subgroup(s) only, otherwise No.
Quality assessment:
Weather from participant location: "Met" if weather was retrieved from participants' actual locations, otherwise "Not Met."
Time spent outside considered: "Not Met" if time spent outside was not measured.
Sufficient length of follow-up: "Met" if outcome data were retrieved during 4 seasons (covering the full range of weather variation), otherwise "Not Met."
Blinding to study aims: "Met" if participants were unaware of study aim/hypothesis, otherwise "Not Met."
Accounted for repeated measures: "Met" if analysis method accounted for repeated measurements within participants, otherwise "Not Met."
Corrected for multiple testing: "Met" if authors adjusted *P* value to correct for multiple testing, otherwise "Not Met."
Reported all results: "Met" if correlation coefficients for significant and nonsignificant findings were reported, otherwise "Not Met."
Reported exact *P* values: "Met" if exact *P* values were reported, otherwise "Not Met."
* Study did not perform formal hypothesis test.
NA, not applicable; NR, not reported.

Table 3

Results, sample size, and quality assessment of longitudinal cohort studies assessing associations between pain and multiple predictors.

	Study	Author-reported association	Sample size	No. of weather variables investigated	Weather from participant location	Time spent outside considered	Length of follow-up	Blinding to study aims	Reported all effect sizes	Reported uncertainty
Met 5 Quality Criteria	Neogi et al.[52]	Yes	619	2	Met	Not met	Met	Met	Met	Met
Met 4 Quality Criteria	Dorleijn et al.[12]	Yes	222	6	Not met	Not met	Met	Met	Met	Met
	Ferreira et al.[20]	No	171	4	Met	Not met	Not met	Met	Met	Met
Met 3 Quality Criteria	Duong et al.[16]	No	1604	4	Not met	Not met	Not met	Met	Met	Met
	Steffens et al.[68]	Yes	993	7	Not met	Not met	Not met	Met	Met	Met
	Beilken et al.[4]	No	981	7	Not met	Not met	Not met	Met	Met	Met
	Timmermans et al.[71]	Yes	810	5	Not met	Not met	Met	NR	Met	Met
	Abasolo et al.[1]	Yes*	245	6	Not met	Not met	Not met	Met	Met	Met
	McAlindon et al.[50]	Yes	200	5	Met	Not met	Not met	Met	Met	Not met
	Çay et al.[10]	No	56	7	Not met	Not met	Not met	Met	Met	Met
	Smedslund et al.[64]	No	50	3	Not met	Not met	Not met	Met	Met	Met
	Fagerlund et al.[18]	Yes	48	3	Not met	Not met	Not met	Met	Met	Met
Met 2 Quality Criteria	Gorin et al.[26]	Yes	75	4	Not met	Not met	Met	Not met	Met	Partially met
	Drane et al.[15]	Yes	53	5	Not met	Not met	Met	Met	Not met	Partially met
	Vergés et al.[73]	Yes*	134	3	Not met	Not met	Not met	Met	Not met	Met
	Smedslund et al.[66]	Yes	36	13	Not met	Not met	Met	Met	Not met	Not met
	Aikman[2]	Yes	25	4	Not met	Not met	Met	Met	Not met	Not met
	Fors and Sexton[23]	No	55	6	Not met	Not met	Not met	Met	Not met	Partially met
Met 1 Quality Criterion	McGorry et al.[51]	Yes	94	8	Not met	Not met	Not met	Met	Not met	Not met
	de Figueiredo et al.[22]	Yes	32	4	Not met	Not met	Not met	Met	Not met	Not met
Did not fully meet any quality criteria	Bossema et al.[7]	No	333	5	Not met	Not met	Not met	Not met	Not met	Partially met
	Brennan et al.[9]	Yes	53	3	Not met	Not met	Not met	NR	Not met	Partially met
	Laborde et al.[45]	Yes*	161	6	Not met	Not met	Not met	Not met	Not met	Not met
	Guedj and Weinberger[29]	Yes*	64	4	Not met	Not met	Not met	NR	Not met	Not met

Author-reported association: Yes, if authors report at least one association between a weather variable and pain, Yes* if authors report an association in subgroup(s) only, otherwise No.
Quality assessment:
Weather from participant location: "Met" if weather was retrieved from participants' actual locations, otherwise "Not Met."
Time spent outside considered: "Not Met" if time spent outside was not measured.
Sufficient length of follow-up: "Met" if outcome data were retrieved during 4 seasons (covering the full range of weather variation), otherwise "Not Met."
Blinding to study aims: "Met" if participants were unaware of study aim/hypothesis, otherwise "Not Met."
Reported all effect sizes: "Met" if effect sizes were reported, both of significant and nonsignificant findings, otherwise "Not Met."
Reported uncertainty: "Met" if confidence intervals were reported, "Partially Met" if confidence intervals were not reported, but readers could calculate them based on reported results, otherwise "Not Met."
NR, not reported.

in some participants only,[44] and 4 did not find evidence for an association.[31,58,63,72] One study met only one quality criterion and did not find an association between weather and pain.[74]

Only one study reduced misclassification of exposure by both retrieving weather from participant location and considering time spent outside.[11] Only one study accounted for repeated measures and corrected for multiple testing, thereby reducing the chance of spurious findings.[77] Reporting of results was often selective; only 2 studies reported results both for significant and nonsignificant findings, including exact P values.[6,61]

Twenty-four longitudinal cohort studies did multivariable analyses of weather and pain. Given their repeated outcome measures, these studies were in a better position to identify and quantify associations between weather and pain. These studies were scored on 6 quality criteria (**Table 3**). One study met 5 criteria and found an association between weather and pain.[52]

Two studies met 4 quality criteria, of which one found an association between the weather and pain[12] and one did not.[20] Nine studies met half of the quality criteria. Five found an association between the weather and pain (Refs.18,50,68,71 at population level; Ref.1 for participants between 50 and 65 years of age only) and 4 did not.[4,10,16,64] Six studies met 2 quality criteria, of which 5 found an association[2,15,26,66] (at population level[73]; in osteoarthritis but not in rheumatoid arthritis). Two studies met one quality criterion, and both found an association.[21,51] Four studies did not fully meet any of the quality criteria. Three found an association[9,29] (at population level[45]; in participants living in an urban area only) and one did not.[7]

Half of the studies had sample sizes larger than 100 participants. Three studies retrieved weather from participant locations,[20,50,52] but none considered time spent outside. Length of follow-up spanned 4 seasons in 7 studies only.[2,12,15,26,52,66,71] Blinding to study aims and reporting all effect sizes were the quality criteria met by most (more than half) of the studies.

In all 3 categories—cross-sectional studies, longitudinal studies estimating correlations between pain and one predictor, and longitudinal studies assessing associations between pain and multiple predictors—clear reporting of results was a problem. This may partially reflect the age of articles, some of which were published in times with different requirements for reporting of scientific results. Some authors, mainly of articles published before the year 2000, did not report effect sizes at all,[11,29,74] only highlighted analyses that resulted in a *P* value lower than a certain threshold value (eg, <0.05), reported effect estimates for significant results only,[22] or did not report exact *P* values.[26,51,77] Second, some studies conducted multivariable analyses and used stepwise selection of variables (see Section 3.8), which automatically rejects nonsignificant candidate variables, resulting in estimates for variables with significant associations in all steps only.[7,10,12,71] Hence, including all studies in a meta-analysis was not possible, and a meta-analysis of a small subset of studies that included required information would introduce reporting bias and possibly publication bias.[47] It was difficult to compare results of different studies even when they were well reported because of heterogeneity in choice of exposure, outcome, and analysis methodology. The subsequent section will consider the details and impact of this heterogeneity.

When comparing study findings as a function of weather variables, we found little consistency. Temperature, atmospheric pressure, relative humidity, and precipitation were investigated by more than half of the studies (**Table 4**). For these weather variables, some studies found an association between that variable and pain, and some studies did not find any association with pain (**Table 4**). Similarly inconsistent findings were reported for wind speed, sunshine, cloud cover, wind gust, and Leuven weather index. The only weather variable that was investigated in multiple studies ($N = 3$) and was consistently not associated with pain was wind direction (**Table 4**).

The remainder of this subsection discusses the results of the six studies that met more than half of the quality criteria. These studies investigated temperature,[12,20,49,52,77] relative humidity,[12,20,52] sunshine hours,[12,49] atmospheric pressure,[12,20,49,77] precipitation,[12,20,41,49,77] and wind speed.[12] All 6 had different outcome measures: self-reported pain on a 0 to 100 visual analog scale (VAS)[12] or 0 to 10 numeric rating scale (NRS),[77] a knee pain exacerbation (2 or larger increase on a 10-point numeric pain rating scale),[20] self-reported presence of chronic widespread pain,[49] a self-reported gout attack (subsequently verified in the participant's medical history[52]), or the proportion of outpatient visits for joint or back pain based on insurance claim data.[41]

For temperature, 2 studies found an association,[49,52] although in opposite directions, and 3 did not.[12,20,77] In one of the 2 studies that found an association, participants were less likely to report chronic widespread pain on days above 17.9˚C, although the association was partially explained by better sleep quality and more positive mood.[49] In the other, participants were at higher risk of gout attacks with temperatures over 15˚C.[52] Of the 3 studies that reported no association, 2 provide no evidence for an association, reporting that a 1˚C increase in temperature was not associated with an increase in pain on a 0 to 100 VAS,[12] or with a very small and nonsignificant (0.00-0.12) correlation coefficients as result of 36 analyses of temperature (mean, minimum, maximum, 1 day lag behind pain report, and 1 day lead before pain symptom).[77] The third study partitioned temperature

Table 4

Study results by weather variable, ordered by number of studies that investigated the weather variable.

Weather variable	No. of studies investigating this variable	No. of studies finding no association with pain (%)	No. of studies finding an association with pain (%)
Temperature	41	21 (51)	20 (49)
Atmospheric pressure	41	20 (49)	21 (51)
Humidity			
Relative humidity	35	16 (46)	19 (54)
Vapor pressure	6	3 (50)	3 (50)
Dew-point temperature	3	2 (67)	1 (33)
Precipitation	30	8 (27)	22 (73)
Wind speed	20	9 (45)	11 (55)
Sunshine	16	5 (31)	11 (69)
Cloud cover	7	3 (43)	4 (57)
Wind direction	3	0 (0)	3 (100)
Wind gust	2	1 (50)	1 (50)
Leuven weather index	2	1 (50)	1 (50)

in 4 categories and reported statistically and clinically significant results: temperatures of >30°C were associated with a two-fold risk of a knee pain exacerbation (odds ratio 2.18, 95% confidence interval [CI] 1.01-4.74).[20] This result, however, was not confirmed in a subsequent trend analysis. Of note, the authors had few observations in the extreme categories (33 with temperature >30°C; 6 with temperature <10°C), hence power to detect an association in those categories was low.[20] Overall, these 6 studies provide modest evidence for an association between temperature and chronic musculoskeletal pain, with evidence for partial mediation by third factors (sleep quality and mood) and potential different directions in different populations.

For relative humidity, one study[12] found an association, and 2[20,52] did not. In the one study that found an association, higher relative humidity was associated with self-reported pain, although it explained less than 1% of the within-participant and between-participant variability, and a 10% change in relative humidity was only associated with a 1-point increase in pain (on a 0-100 VAS).[12] The 2 negative studies, however, did provide some evidence for an association. One found that relative humidity may "possibly" be associated with increased risk of gout attacks, although they only had enough power to determine the shape of the relationship with certainty (J-shaped: both extremes of relative humidity associated with increased risk).[52] The other study that did not find an association, divided relative humidity into tertile categories (<59%, 59-79% as referent, and 79-100%).[20] For the lowest and highest categories, CIs spanned 1. For the highest category, the odds ratio was 1.25 (95% CI 0.72-2.19). These results do not exclude an association between humidity and pain, especially as a humidity effect may not fall exactly in the bins chosen by the authors.

For sunshine hours, one study reported an association: participants were less likely to report chronic widespread pain on days with 5.8 sunshine hours (compared with 0 sunshine hours), although again partially explained by better sleep quality and more positive mood.[49] The other did not find a significant association, but reported a non-statistically significant estimate of −0.1 (95% CI −0.3 to 0.1): 1 extra hour of sunshine was associated with a 1-point pain increase on a 100-point VAS.[12] As the variability of sunshine hours was low (median 3.8; range 1.1-7.5), this effect is indeed of negligible clinical importance.

Results seemed consistent for atmospheric pressure, precipitation, and wind speed: none of the studies found a significant association between their pain outcome and those weather variables. For atmospheric pressure, 2 studies gave no evidence for an association between atmospheric pressure and pain (small and nonsignificant correlation coefficients).[12,49] The remaining 2 studies investigated pressure in 5 categories (although with slightly different cutoffs) and had contradictory findings.[20,77] One reported lower odds of chronic widespread pain with higher pressure (lowest odds—and only significant odds ratio—for the middle category, highest odds with pressure <1007 mbar and >1023 mbar).[77] The other study reported the lowest odds of knee pain exacerbations with the lowest and highest level of pressure (<1010 and >1024 hPa; not statistically significant).[20] For precipitation, the 5 studies did not provide evidence for an association with pain, no matter how exposure (mm[12]; cm[77]; precipitation categories[20,49]; rainy days or weeks vs nonrainy days or weeks[41]) and outcome were defined. Wind speed was investigated by one study only, which found that a 1 m per second increase in wind speed was associated with a 2-point reduction in pain (on a 100-point scale).[12] That this coefficient did not reach statistical significance (95% CI −0.5 to 0.1), may indicate that the study did not have sufficient power to detect an association.

Overall, the 6 studies of highest quality demonstrate inconsistent findings. If the weather–pain association differs between musculoskeletal conditions, these seemingly conflicting results may of course reflect actual differences in existence, strength, or directions of associations. Inconsistency in these findings may also be partially due to methodological and analytical differences between the studies. In Sections 3.5 and 3.6, we describe the sources of variation in weather data collection and analysis. In addition, we critically reflect on the consequences of these for the study results.

3.3. Outcome: pain measures

The 36 studies that collected self-reported pain severity most often used a VAS or 10-point NRS to collect self-reported pain severity (27/36, 75%; **Table 5**). Other measures were a Likert scale,[7,69] a 3-point nominal scale,[29,59] the 5-point pain intensity rating scale from the McGill questionnaire,[45] a Yes/No question about the presence of pain,[49] Short Form 36 Health Questionnaire,[25] or the 100-point pain score from the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC[12,50]). For measuring self-reported pain severity, previous studies have shown that the VAS, NRS, and other pain scales with 4 or 5 answer categories are similar in terms of reliability and the underlying pain concept they measure.[14,42]

Seven studies used electronic medical records databases,[1,3,38,52,68] a drug-trial database,[4] and an insurance-claims database[41] to identify hospital visits for pain-related complaints. Usage of routine data from these databases has a range of limitations.[55] A weakness in these types of studies is the often implicit assumption that participants always go to the hospital in the case of a painful event, do so shortly after the event, and that events are adequately and systematically coded.

3.4. Outcome: frequency of pain reports

In the longitudinal studies, frequency of self-reported pain varied from once every 2 weeks to 4 times a day. Collecting pain severity records on a daily basis has several advantages. First, daily reporting of pain is consistent with the time scale of daily weather changes that anecdotally are reported by those who believe in an association between their pain and the weather. Second, there is discrepancy between daily and weekly pain recall, with daily pain reporting deemed more reliable.[24] Third, frequent pain records enable correction for individual patterns in pain reporting and behavior through within-participant analyses (eg, outcome defined as deviation from participants' personal mean and inclusion of personal intercepts in regression analysis), which minimizes the problem that one person's "mild pain" might be another's "severe pain." Pain reporting multiple times a day enables investigating short-term changes in pain, although it may hamper detection of an association; temporally close pain reports are strongly correlated,[6,15,53] and weather data may not always be available on the same time scale.

3.5. Exposure: collection of weather

The 43 studies investigated a median of 5 weather variables (range 1−13; **Table 5**). Weather data were retrieved from weather stations operated by the meteorological services of each country, although the exact method of data retrieval was not always

Table 5

Characteristics, results, and methods of included studies.

Design	Study	Outcome Measure	Outcome Freq	Outcome Freq	Change	Lags	T	P	H(R)	PR	WS	S	CC	H(V)	H(D)	WD	LWI	WG
Cross-sectional	Arber et al.[3]	EMR	NA	2× daily		X	X	X										
	Glaser et al.[25]	SF-36	Once	NR			X	X	X	X		X		X	X			
	Işik et al.[38]	EMR	NA	Daily			X	X	X	X	X					X		
	Jena et al.[47]	EMR	NA	Daily		X				X								
	Macfarlane et al.[49]	Yes/No	Once	Daily			X	X		X		X						
	Peultier et al.[56]	VAS	Once	Daily			X	X	X	X	X	X						
Longitudinal (correlations)	De Blecourt et al.[6]	NRS	Weekly	Weekly		X	X	X	X	X	X		X	X				
	Dequeker and Wuestenraed[11]	VAS	4× daily	3× daily	X		X	X	X		X		X				X	
	Hagglund et al.[31]	VAS	NR	Daily	X		X	X			X	X						
	Koyama et al.[44]	VAS	Daily	Daily	X		X	X	X	X		X						
	Patberg et al.[53]	NRS	Daily	Daily		X	X	X	X		X			X				
	Redelmeier and Tversky[58]	NR	Fortnightly	2× daily		X	X	X	X									
	Rentschler et al.[59]	3-point	Daily	Daily		X		X		X								
	Savage et al.[61]	VAS	Daily	Daily			X	X	X	X	X	X						
	Sibley[63]	VAS	Daily	2× daily		X	X	X	X	X	X							
	Strusberg et al.[69]	VAS, Likert	Daily	2× daily	X	X	X	X	X									
	Viitanen et al.[74]	VAS	3× daily	Daily			X	X	X				X					
	Wilder et al.[77]	NRS	Weekly	Daily		X	X	X		X								
Longitudinal (multivariable)	Aikman[2]	NRS	4× daily	2-4× daily			X	X		X	X							
	Bossema et al.[7]	Likert	Daily	Daily	X	X	X	X	X	X		X						
	Brennan et al.[9]	VAS	Daily	Daily	X		X	X		X								
	Çay et al.[10]	VAS	Daily	Daily		X	X	X	X	X	X	X		X				
	Dorleijn et al.[12]	WOMAC	Quarterly	Quarterly		X	X	X	X	X	X	X						
	Drane et al.[15]	VAS	Daily	3× daily	X	X	X	X	X	X	X	X	X		X			
	Duong et al.[16]	NRS	Daily	Hourly	X	X	X	X	X	X								
	Fagerlund et al.[18]	NRS	3× daily	3× daily			X	X	X									
	Fors and Sexton[23]	VAS	Daily	Daily	X	X	X	X	X		X	X	X					
	Gorin et al.[26]	VAS	Daily	Daily	X	X	X	X	X			X						
	Guedj and Weinberger[29]	3-point	Daily	Daily			X	X	X	X								
	Laborde et al.[45]	McGill	NR	≤8× daily			X	X	X	X	X	X						
	McAlindon et al.[50]	WOMAC	Fortnightly	Daily	X		X	X	X	X					X			
	McGorry et al.[51]	NRS	Daily	Daily	X	X	X	X	X	X	X	X		X			X	
	Queiroga et al., 2013	VAS	3× week	Daily		X	X	X	X	X								
	Redelmeier and Tversky[58]	NR	Fortnightly	2× daily		X	X	X	X									
	Rentschler et al.[59]	3-point	Daily	Daily		X		X		X								
	Sibley[63]	VAS	Daily	2× daily		X	X	X	X	X	X							
	Smedslund et al.[66]	VAS	Daily	Daily		X	X	X	X	X	X	X	X	X	X			
	Smedslund et al.[64]	NRS	3× daily	3× daily	X	X	X	X	X									
	Timmermans et al.[71]	NRS	Daily	Daily	X		X	X	X	X	X							
	Tsai et al.[72]	VAS	Daily	Daily	X	X	X	X	X	X	X							
	Vergés et al.[73]	VAS	Daily	Daily			X	X	X									

(*continued on next page*)

Table 5 *(continued)*

Design	Study	Outcome Measure	Freq	Outcome Freq	Change	Lags	Weather variables T	P	H(R)	PR	WS	S	CC	H(V)	H(D)	WD	LWI	WG
Longitudinal (case-crossover)	Abasolo et al.[1]	EMR	NA	NR		X	X	X	X	X		X	X					
	Beilken et al.[4]	Drug trial	NA	Daily	X	X	X	X	X	X	X					X		X
	Ferreira et al.[20]	NRS	NA	Daily		X	X	X	X	X								
	Neogi et al.[52]	EMR	NA	Daily			X		X									
	Steffens et al.[68]	EMR	NA	Hourly	X		X	X	X	X	X					X		X

Ordered by study design, result, and alphabetical order of name of first author.
Outcome measures: Likert scale (Likert), visual analog scale (VAS), numeric rating scale (NRS), 3-point scale (3-point), McGill pain intensity rating scale (McGill), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), short form 36 questionnaire (SF-36), Yes/No question (Yes/No), visit for arthritic pain in electronic medical record (EMR) or not reported (NR).
Outcome—frequency of data collection: Frequency of obtaining self-reported pain severity (units).
Exposure—frequency of data collection: Frequency of obtaining weather data (units).
Weather change: Was change in weather analysed?
Weather lag: Was lagged effect of weather analysed?
Weather variables: Number of weather variables considered; subsequent columns show which weather variables were considered (X if analysed in study).
CC, Cloud Cover; H(D), Humidity (Dew Point Temperature); H(R), Humidity (Relative); H(V), Humidity (Vapour Pressure); LWI, Leuven Weather Index; P, Pressure; PR, Precipitation; S, Sunshine; T, Temperature; WD, Wind Direction; WG, Wind Gust; WS, Wind Speed.

specified. Weather data were treated differently across the studies. For example, temperature was analyzed in 1 of 3 ways: by time of day (eg, values at midnight, 9 AM or noon), by a single metric per day (eg, the minimum, maximum, average, range, difference or change), or by categories for different ranges in temperature. For humidity, most studies used relative measures (relative humidity or dew-point temperature depression), and a minority used absolute measures (direct moisture content expressed as dew-point temperature, mixing ratio, or vapor pressure). Relative humidity (the ratio of the vapor pressure to the saturated vapor pressure at a given temperature) is a function of absolute humidity and temperature and therefore changes whenever temperature changes (within the day as well as between days). Previous research shows that changes in absolute humidity and relative humidity have different physiological effects on the human body,[36] indicating that both may be associated with pain perception.

The studies occurred in a number of places around the world. Some study locations were in the tropics or subtropics, where participants would experience a warm climate with little day-to-day or season-to-season variability: Madrid,[1] Brazil,[21] Sydney,[4,15,68] and Florida.[77] Other study locations were in the colder, more variable climates of the midlatitudes: The Netherlands,[7,12,53] Ireland,[9,61] Belgium,[11] Norway,[18,23,64,66,74] Connecticut in the United States,[26] Japan,[44] and northwest England.[49] Thus, the type of climate and the extremes of weather that participants are exposed to vary between the studies. Studies in certain climates cannot be used to investigate some types of weather extremes on participants' pain (eg, cold-sensitive individuals would be less likely to experience a painful event in a tropical location). This limitation also applies to studies that did not collect data over all seasons (see section "Study characteristics").

3.6. Exposure: handling of weather data

All studies considered the weather values on the same day as the participants reported their pain severity, if any. Most studies (24/43, 56%) investigated lags (weather preceding pain) and leads (pain preceding weather). Typically, these lags and leads were for only 1 day, but occasionally researchers investigated multiple days lag and lead such as 2 days,[58] 3 days,[15] or 180 days,[53] or even multiple hours lag and lead, such as 8 hours[64] and 12 hours.[58] A minority of studies (16/43; 39%) investigated change in weather, usually "change compared to yesterday," but occasionally investigated more granular changes (eg, 6-hour changes[15]).

How the weather variables were analyzed also varied among the 43 studies. Some studies reported univariable analyses (eg, "the effect of temperature"), whereas others reported multivariable analyses (eg, "the effect of temperature keeping relative humidity and pressure constant"). A challenge is that describing the state of the atmosphere requires multiple weather variables, but these variables can be correlated ("multicollinearity"). The analysis of multiple correlated variables can be problematic as many analysis methods depend on the assumption that analyzed variables are independent. If highly linearly correlated weather variables are used together as predictors in a regression model, this assumption is violated. As a result, the individual coefficients that quantify the size of effect may be biased and underestimate the association between weather variable and outcome. The strongest linearly related weather variables are temperature with an absolute measure of humidity (eg, dew point) and relative humidity. If the values of any 2 are known, the third can be calculated. It is therefore advisable not to use these together as predictors in a regression model. Similarly, vapour pressure (another relative measure of humidity) is derived from dew-point temperature, and the wet-bulb temperature is dependent on both temperature and relative humidity. Of 6 studies investigating more than one of these variables, 3 used them together in a regression model, potentially violating the assumption of independent exposure of variables.[25,50,65]

To address this challenge of multicollinearity, 2 studies performed principal component analyses,[23,51] where associations between the outcomes and principal components (linear combinations of weather parameters) are reported. The disadvantage of principal components is that their relationship to weather variables such as temperature and pressure is difficult to understand. Two other studies use the Leuven weather index,[11,51] a weighted sum of variables chosen by the lay public (sunshine, precipitation duration, mean temperature, and mean wind velocity). The origin, method of construction, and validation of this weather index is unclear, putting it potentially at odds with the principles of proper weather indices.[13]

3.7. Misclassification of exposure

A few studies (10/43, 23%) reported efforts to reduce misclassification of exposure (measurement error: the recorded weather not representing the weather that the participant was exposed to). Two possible causes of exposure misclassification are (1) the participant was not near the location of the weather measurement and (2) the participant was at/close to the location of the weather measurement but was not exposed to the weather. Studies usually collected weather data from the city or area where the study took place or the recruited participants lived and assumed that they stayed within that area during the study. Ten studies reduced misclassification of exposure by excluding days if participants reported being outside the city or area,[22,63,69] collecting data while participants were at a specific location[11,56,59,61] or having participants report postal code at the time of the pain report and retrieving weather information from there.[20,50,52] In studies that did not verify the location of participants—for example, because they performed secondary analyses of data collected for other purposes—the extent of misclassification of exposure depends on the climatic zone and local altitude differences. The weather may vary between nearby places, and the distance between the weather station and the participant may cause misclassification of exposure. This misclassification of exposure may be differential (ie, related to the outcome). Specifically, participants who travel less when they are in more pain may have their weather exposure more faithfully represented.

Misclassification because participants were indoors may have occurred in all studies. One study investigated hospitalized patients who always stayed indoors.[11] This study measured humidity and temperature indoors and retrieved outdoor weather data. Although the study could have addressed misclassification by analyzing indoor weather variables, it only analyzed the outdoor weather variables. The amount of time people stay indoors may be influenced by the weather, as people may stay inside during weather extremes such as low temperatures.[50] In addition, housing, heating/air conditioning, and clothing may expose people to more stable temperature and humidity than weather stations measure.[53] Humidity penetrates indoors to some extent, but in cooler climates, the inside is usually more humid than outside, as a result of respiration, cooking, and use of water. Atmospheric pressure indoors and outdoors are similar, but changes in pressure from changing altitude (even by going up staircases) can exceed daily pressure changes. Specifically, an increase in altitude of 8 m (the height of going up about 2 floors in a building) near sea level is roughly equivalent to a pressure change of 1 mbar, whereas the daily pressure change in the midlatitudes may be several mbar a day.[5]

3.8. Statistical methods to link pain to weather

The 36 longitudinal cohort studies used 2 types of statistical methods to link pain reports to weather variables (method not reported in 2 studies): correlation coefficients or regression methods. Twelve studies (12/30; 32%) calculated correlation coefficients of single weather variables and pain reports. However, correlation analyses do not account for the autocorrelation of pain measures on consecutive days and cannot adjust for covariates. In addition, studies using correlation analyses are at high risk of spurious findings (type I errors[27]) because they investigate up to 342 associations.[11] Some studies[6,31] did a Bonferroni correction for multiple comparisons and decreased the cutoff for the *P* value to 0.003[31] and 0.025.[6] Greenland[27] describes that there is no widely accepted solution to the problem of multiple comparisons and that a Bonferroni correction, although reducing false positives, favors extremely significant associations that arise from extreme errors (rather than extreme effects).

Twenty-four studies used regression methods (9 multiple regression, 5 conditional logistic regression, 4 generalized linear models, 3 autoregressive models, and 3 multilevel models), sometimes using correlation coefficients, but only to select predictors from a set of candidate variables. Selecting predictors is a challenge: inclusion of correlated predictors inflates standard errors of regression coefficients (and may induce bias). Stepwise selection of predictors, however, only results in the best model if all individual predictors sequentially and individually meet the screening criterion. Hence, stepwise selection of predictors is vulnerable to missing good alternative models.[75] Coefficients that are overestimated are more likely to be included in the final model. Stepwise variable selection therefore results in too high regression coefficients and too small *P* values and, in case of multicollinearity, may arbitrarily select some but not all of the correlated variables that contribute.[32] Of note, frequent usage of stepwise selection is not unique to this area. Other research shows that in leading journals, 20 to 60% of studies using multiple regression also use stepwise selection, despite statisticians' concerns.[67]

The studies that found associations in subgroups may be at higher risk of spurious findings. As protocols were not available for the studies, it was not possible to assess whether subgroup analyses had been specified a priori. In addition, the studies did not provide a causal framework that informed the subgroup analyses. Two studies at least provided clear hypotheses that weather and pain may be more strongly related in patients with definite radiologic hip osteoarthritis (compared to those with early radiologic hip osteoarthritis[12]), and that the association between weather and pain may be different between people in an urban climate (characterized by, eg, pollution and lack of vegetation) compared with a rural climate.[45] Subgroup analyses based on participants' diagnoses could be useful, as associations with the weather may be dependent on the underlying mechanisms of the musculoskeletal disease (eg, inflammation, breakdown of joint cartilage and bone). Analyses stratified by disease, however, would rely on the assumption that diagnoses are reliable (which, in case of self-reported diagnoses, may require ascertainment of diagnosis through, for example, electronic medical records) and that participants have one diagnosis only (which may not be valid, especially for older multimorbid populations).

Five studies that analysed the association between weather and pain for individual participants are at especially high risk of spurious associations. One study did not perform a formal hypothesis test.[59] Three did not correct for multiple comparisons nor report all coefficients or exact P values.[11,29,44] Only one study corrected for multiple comparisons and had a carefully stated conclusion, namely that some participants were weather sensitive according to their criteria, but that they had not found distinct groups of weather-sensitive participants.[66]

The 6 cross-sectional studies did not take repeated outcome measures and quantified between-participant differences in pain and weather. It is therefore difficult to distinguish between seasonal effects and the weather, and the relations they found may be driven by seasonal trends. One study addressed this issue by conducting a subanalysis for self-reported pain severity within autumn and spring (seasons with higher variability in weather conditions) only, which provided some though not conclusive evidence of a weather effect within those seasons.[49]

3.9. Adjustment for covariates

Longitudinal regression models allow for adjustment for covariates, which can help eliminate confounding and decompose an effect into a direct effect and indirect effect. Adding covariates to the model, however, comes with a risk: incorrectly adjusting for a variable can create an artificial noncausal relation between exposure and outcome (for example, if the variable is a collider, a common effect of exposure and outcome, rather than a confounder, a common cause of exposure and outcome).[28] In the reviewed longitudinal studies using regression methods, some did not include any covariates, whereas others included up to 11 of 38 different covariates. It is difficult to assess whether adjustment for all these covariates is justified, as few studies report on their hypothesized causal framework. Having such a framework is important as it provides evidence that, for example, a potential confounder is plausible as a cause of both exposure and outcome.[76] Most studies neither explicitly specify the role of a covariate (eg, as confounder or mediator) nor provide evidence that it is plausible. Some studies specify whether a variable was considered confounder or mediator but do not provide evidence of plausibility. An exception is a study where low mood, poor sleep quality, and lack of exercise are explicitly named as mediators, with references to studies that have shown associations between those and chronic pain onset.[49]

Confounding can lead to spurious associations or absence of evidence for associations between weather and pain due to the presence of common causes of exposure and outcome ("confounders," in this case variables that influence both pain and exposure to weather but are not on the causal pathway). Confounding can be controlled for by adding confounders to the regression models as covariates.[34] Some covariates are indeed plausible confounders, such as variables related to disease severity,[2,7,9,16,18,23,29,50,64,71] patterns in pain reporting,[7,15,50] or participant characteristics or behavior,[7,16,23,50,69,71,74] as they may influence both pain severity and exposure to weather. For other covariates, their status as confounders or mediators is unclear: marital status,[7] health insurance, number of previous back pain episodes and paid compensation,[16] psychological status or depression at baseline,[10,23,71] sex or gender,[16,50,71,74] and weight.[74] These do not seem to be causes of weather or influencers of exposure to weather.

Moderators are variables that change the strength or direction of associations. Analyzing interaction effects of a moderator variable will quantify these relationships. Moderators should be identified a priori, based on specific evidence or theory, and if baseline factors are investigated, these should be of adequate reliability and validity.[57] One study included many of the above variables (8 patient characteristics, season, and degree of weather variation) as moderator variables in order to explain significant between-participant variation in the association between weather and pain but did not find significant interaction effects.[7] Various other studies also investigated moderating effects of participant characteristics or behavior[18,23], disease duration,[23,64], patient group (specific diagnosis, age group, region, and race),[41] or baseline pain.[20] Three studies[15,45,51] investigated the effect of self-reported weather sensitivity on the weather–pain association, a plausible moderator, although this resulted in small sample sizes of 25 to 32 persons. In addition, some studies investigated potential moderating effects of weather variables.[20,50,71] One study tested interactions between all weather variables (temperature, atmospheric pressure, relative humidity, precipitation, and wind speed) and found that the effect of humidity on pain was stronger at lower temperatures and absent if temperature was higher than 16.9˚C).[71] Others found no significant effect.[20,50] As the included studies provided limited rationale behind selecting variables as moderators, it is difficult to assess whether the variables had been chosen appropriately. As the weather is largely determined by the 4 state variables of temperature, humidity, atmospheric pressure, and wind speed, moderating effects of combinations of those could indeed be plausible.

Mediators are variables that are on the causal pathway from exposure to outcome. Adding mediators to the model as covariates helps quantify the direct effect of the association between weather and pain explained by paths other than the mediator. An example of a mediator would be mood, if weather was associated with mood, and mood was in turn associated with pain. Correcting for mood would isolate the association between weather and pain explained by other pathways than mood. In some studies, sleep quality, (depressive) mood, and/or physical activity were measured at the same frequency as pain severity.[6,7,64] One study used these additional measures as secondary outcomes, rather than to investigate confounding.[6] The others did not find evidence for mediation of the association between weather and pain by mood/psychological status.[7,64] One cross-sectional study[49] found that participants were less likely to report pain on days with sunshine and higher temperatures, and that this was partly explained by more exercise, better sleep quality, and more positive mood on these days (ie, evidence for mediation). To unravel the association between weather and pain in longitudinal studies, it would be good to measure these mediators frequently, as exercise, sleep quality, and mood are time-varying.

4. Discussion

Studies investigating the association between weather and chronic musculoskeletal pain found variable results. The majority found at least one association between a weather variable and chronic pain levels. This result may partly reflect publication bias (selective submission or publication of positive findings[17]) or spurious findings due to testing of many hypotheses. The highest consistency, and highest percentage of positive studies, was found among 6 cross-sectional studies. As these compared weather and pain between participants, rather than within participants, these were not well-placed to distinguish larger-scale seasonal effects from day-to-day weather conditions. In addition, most cross-sectional studies relied on strong assumptions related to secondary use of health databases. Half of the 12 studies investigating correlations between single weather variables and self-reported pain found an association, and half did not. These studies met the fewest of the quality-assessment criteria and investigated the fewest participants. Hence, they were at highest risk of bias and potentially underpowered, making it difficult to draw strong conclusions from their exploratory work. Of 24 studies conducting multivariable analyses of weather and self-reported pain, two-thirds found a positive result. Although the quality of reporting was higher and methods were more appropriate for the context, most were still at high risk of misclassification of exposure. We were not able to perform a meta-analysis because of the heterogeneity of the body of evidence and poor quality of results reporting (few studies reporting all effect sizes and measures of uncertainty or significance).

Most studies investigated 5 or more weather variables and investigated temperature, atmospheric pressure, relative humidity, and precipitation. Wind speed, sunshine, cloud cover, wind gust, wind direction, and Leuven weather index were investigated by a minority of studies. Some studies found an association between weather and pain, whereas others did not. Even per weather variable, results were inconsistent.

Explanations for this inconsistency are the differences in study design, definition of outcome and exposure, and analysis methods. Most studies were longitudinal and investigated self-reported pain as outcome, but there were large differences in sample sizes, outcome definition, ascertainment of exposure, and statistical method.

4.1. Linking weather and pain: lessons learnt for future studies

Because of various limitations to study quality, it has not been possible to reach a robust conclusion to the age-old question whether the weather influences pain. The best that we can say, based on studies that did not find an effect or reported very small effect sizes, is that if an association exists, it is not likely to be strong. Future studies can build upon the existing body of literature by increasing their ability to detect an association between weather and pain if one exists yet reducing the probability of spurious findings, specifically by increasing power and reducing noise. We now describe specific recommendations for future studies, also shown in **Table 6**.

First, studies should investigate sufficiently large sample sizes. Most studies had fewer than 100 participants, and few studies had more than 300 participants. Because patients' daily pain can be affected by nonweather factors (eg, medication intake, physical exercise, and sleep quality), a larger sample size is required to detect possible associations. If associations only exist in subpopulations (eg, per disease), power to detect these associations will be further diminished if the original number of participants is relatively low.

Second, studies should investigate moderators and confounders that, if uncorrected, may dilute or inflate any association. It is a challenge to specify moderators and confounders; some variables were analysed as confounders in some studies and as mediators in other studies. Only one study provided evidence for their choice of lack of exercise, low mood, and poor sleep quality as plausible mediators.[49] To enable correction for confounding and investigation of moderators, researchers should focus on more sophisticated models accounting for the longitudinal nature of pain reports rather than only performing exploratory analyses of correlations between variables.

Table 6

Recommendations for future studies investigating the association between weather conditions and chronic musculoskeletal pain.

Study design	• Large sample size, especially if interested in associations in subpopulations only • Adequate length of follow-up: outcome data collection during all seasons
Measuring outcome	• Frequent self-reported pain, method with sufficient variability in pain measure such as VAS or NRS
Measuring exposure	• Retrieve weather data from participant location • Account for time spent outside • Misclassification of exposure will further depend on variability in climate and altitude differences.
Analysis methods	• Longitudinal analysis method that enables correction for confounders and considers moderation and mediation • Investigate multicollinearity: refrain from including strongly related weather variables such as temperature and multiple measures of humidity in multivariable models • Consider discerning day-to-day weather conditions from seasonality, for example, by stratifying by season • Specify which weather variables are of interest and justify the choice where possible • Define and justify how weather data will be modelled for the analysis. Consider absolute values (eg, daily mean and daily maximum) and changes (eg, change from yesterday to today in daily mean) • Specify the period of interest where exposures are considered to influence the outcome (eg, on the same day, or a lagged effect of 1 day, 2 days, …)
Reporting	• Reporting should follow existing reporting guidelines for observational studies (eg, STROBE). Specifically, future studies should: • Distinguish a priori from post hoc analyses • Report effect sizes as well as measures of uncertainty • Specify whether covariates are considered confounders, mediators, or moderators and provide evidence for choice

NRS, numeric rating scale.

Third, researchers should choose their measure and analysis of self-reported pain with care. To detect an association, it is important to have sufficient variability in a pain measure (hence a 10-point or 10-cm validated scale may be better than a Yes/No question) and account for individual differences in reporting pain and the autocorrelation between subsequent pain measures within participants.

Fourth, measurement and analysis of exposure data can be improved in various ways. Researchers should observe participants while exposed to the full range of weather types (ideally during all seasons). Also, they should reduce misclassification of exposure as much as possible. Few previous studies verified that weather measurements were taken at the location of the participant, sometimes because authors conducted secondary analyses of data collected for other purposes, or possibly because of limited availability of tools or resources to ascertain exposure to the weather. The extent of misclassification depends on the mobility of the participant and the variability of the local climate in space and time. No studies accounted for the extent to which the participants were exposed to outside weather conditions, which may moderate the association between weather and pain. Of the most frequently investigated weather variables, precipitation, temperature, and humidity will be most affected by the amount of time spent outdoors. Wherever possible, researchers should aim to distinguish between day-to-day weather conditions and seasonality, for example, by considering associations within the same season.

Finally, researchers should consider multicollinearity when performing multivariable analyses. Investigating strongly related weather variables would violate the assumption of independent exposure variables.

Researchers can reduce the probability of spurious findings in various ways. The 43 investigated studies, especially those calculating correlation coefficients, generally tested many different hypotheses. As the quality of results reporting was poor and protocols for the 43 studies were not available, it was impossible to ascertain that analyses had been specified a priori. It is important that researchers clearly and transparently distinguish between a priori analyses and post hoc analyses and, if necessary, correct for multiple testing. Another potential source of spurious findings or biased results, specifically in studies using regression methods, is including covariates that are colliders rather than confounders and mediators, or using stepwise selection of covariates. Researchers should clearly specify whether a variable is considered a confounder, mediator, or moderator (and ascertain it is not a collider). Ideally, researchers should provide evidence for their choice in the form of references to literature or a directed acyclic graph. Based on existing evidence, we cannot exclude, nor strongly endorse, possible effects of absolute weather values, changes in weather, lagged weather, or any specific weather variables.

4.2. Strengths and limitations

A strength of this review is the systematic search to locate existing evidence on the association between weather and chronic musculoskeletal pain severity. The search strategy was not limited to a specific musculoskeletal condition, resulting in studies not considered by previous reviews. In addition, data extraction encompassed both study findings and study methods. This enabled us to explore how study methods may have influenced the lack of scientific consensus. Although a meta-analysis would have been useful, heterogeneity in study design and reporting of results did not allow for this possibility. A limitation of our study is that selection of studies and extraction of data were conducted by one author. Although uncertainties were discussed among the authors, we acknowledge that independent data extraction by 2 authors is considered preferable.

4.3. Potential mechanisms of weather influences on pain

This narrative review shows that the association between weather and pain has been difficult to characterize. There is lack of consensus on the existence of an association between the weather and pain, and a lack of theory as to how the weather may influence arthritic pains. Previous studies discuss various mechanisms. First, it has been suggested that any association might be caused by confirmation bias. Many participants strongly believe in a weather–pain relationship, and they may perceive higher pain levels under certain weather conditions because of their suspicions.[18,26] Although participants can be blinded to study aims, they cannot be blinded to the weather conditions, so a risk of confirmation bias always exists. Some weather circumstances or variables are more at risk of confirmation bias than others. Although people may generally recognize when it is raining, changes in variables such as atmospheric pressure may be less obvious. Second, weather conditions may be a proxy for seasonal patterns, which may be associated with chronic pain because of changes in exposure to vitamin D,[8] in physical activity, sleep and other patterns of daily life or mood,[19,33,40] or in disease activity,[37] for example. Third, if weather conditions influence pain severity, the physiological mechanisms responsible are still unclear. Authors of observational and experimental studies in humans, as well as rats and cadavers, have suggested various hypotheses. One hypothesis is that scar tissue may respond differently to certain weather conditions, such as variations in weather, or cold and damp weather.[35,40] Another hypothesis is that nociceptive nerve fibers, which are more sensitive in arthritic patients, may be affected by low pressure,[60] stiffness,[40] or small movements caused by changes in temperature and pressure.[40] A cadaver study suggested that fluctuations in atmospheric pressure may destabilize joint stability (specifically of the hip), and that it may aggravate pain by influencing movement of intracapsular fluid.[78]

In conclusion, existing studies of the association between weather and pain do not yet provide conclusive evidence to confirm or deny such relationship. The recommendations for future research provided in this review will hopefully make future studies more effective in characterizing the association between weather and pain. Insights into this association could potentially help patients living with arthritis better manage their pain, help clinicians understand sources of variation in pain better, and provide researchers with hypotheses for fundamental research into mechanisms of arthritic pain. In addition, these insights may help elucidate whether patients with arthritis living in midlatitude climates would benefit from prescriptions to Spain.

Conflict of interest statement

W.G. Dixon has received consultancy fees from Bayer and Google unrelated to this study.The remaining authors have no conflicts of interest to disclose.

Acknowledgements

This work was supported by a Medical Research Council doctoral training partnership (grant number MR/N013751/1 to A.L. Beukenhorst), a Natural Environment Research Council UK (grant numbers NE/I005234/1, NE/I026545/1, and NE/N003918/1 to D.M. Schultz) and supported by the Centre for Epidemiology Versus Arthritis (grant number 21755) and the NIHR Manchester Biomedical Research Centre.

Appendix A. Supplemental digital content

Supplemental digital content associated with this article can be found online at http://links.lww.com/PAIN/A932.

Article history:
Received 24 May 2019
Received in revised form 25 November 2019
Accepted 3 December 2019
Available online 20 December 2019

References

[1] Abasolo L, Tobías A, Leon L, Carmona L, Fernandez-Rueda JL, Rodriguez AB, Fernandez-Gutierrez B, Jover JA. Weather conditions may worsen symptoms in rheumatoid arthritis patients: the possible effect of temperature. Reumatol Clin 2013;9:226–8.

[2] Aikman H. The association between arthritis and the weather. Int J Biometeorol 1997;40:192–9.

[3] Arber N, Vaturi M, Schapiro JM, Jelin N, Weinberger A. Effect of weather conditions on acute gouty arthritis. Scand J Rheumatol 1994;23:22–4.

[4] Beilken K, Hancock MJ, Maher CG, Li Q, Steffens D. Acute low back pain? Do not blame the weather-A case-crossover study. Pain Med 2017;18:1139–44.

[5] Blackmon ML, Wallace JM, Lau NC, Mullen SL. An observational study of the Northern Hemisphere Wintertime Circulation. J Atmos Sci 2002;34:1040–53.

[6] De Blecourt ACE, Knipping AA, De Voogd N, Van Rijswijk MH. Weather conditions and complaints in fibromyalgia. J Rheumatol 1993;20:1932–4.

[7] Bossema ER, Van Middendorp H, Jacobs JWG, Bijlsma JWJ, Geenen R. Influence of weather on daily symptoms of pain and fatigue in female patients with fibromyalgia: a multilevel regression analysis. Arthritis Care Res 2013;65:1019–25.

[8] Breivik H. Whether the weather influences pain: high prevalence of chronic pain in Iceland and Norway: common genes? Or lack of sunshine and vitamin D? Scand J Pain 2010;1:149–50.

[9] Brennan SA, Ryan K, Harney T, Gormley C, Rahim NA, Shannon F. Influence of barometric pressure on pain severity in end stage osteoarthritis. Ir J Med Sci 2010;179:S40–1.

[10] Çay HF, Sezer I, Firat MZ, Kaçar C. Which is the dominant factor for perception of rheumatic pain: meteorology or psychology? Rheumatol Int 2011;31:377–85.

[11] Dequeker J, Wuestenraed L. The effect of biometeorological factors on Ritchie articular index and pain in rheumatoid arthritis. Scand J Rheumatol 1986;15:280–4.

[12] Dorleijn DMJ, Luijsterburg PAJ, Burdorf A, Rozendaal RM, Verhaar JAN, Bos PK, Bierma-Zeinstra SMA. Associations between weather conditions and clinical symptoms in patients with hip osteoarthritis: a 2-year cohort study. PAIN 2014;155:808–13.

[13] Doswell C, Schultz DM. On the use of indices and parameters in forecasting severe storms. Electron J Sev Storms Meteorol 2006;1:1–22.

[14] Downie WW, Leatham PA, Rhind VM, Wright V, Branco JA, Anderson JA. Studies with pain rating scales. Ann Rheum Dis 1978;37:378–81.

[15] Drane D, Berry G, Bieri D, Mcfarlane AC, Brooks P. The association between external weather conditions and pain and stiffness in women with rheumatoid arthritis. J Rheumatol 1997;24:1309–16.

[16] Duong V, Maher CG, Steffens D, Li Q, Hancock MJ. Does weather affect daily pain intensity levels in patients with acute low back pain? A prospective cohort study. Rheumatol Int 2016;36:679–84.

[17] Dwan K, Altman DG, Arnaiz JA, Bloom J, Chan AW, Cronin E, Decullier E, Easterbrook PJ, Von Elm E, Gamble C, Ghersi D, Ioannidis JPA, Simes J, Williamson PR. Systematic review of the empirical evidence of study publication bias and outcome reporting bias. PLoS One 2008;8:1–37.

[18] Fagerlund AJ, Iversen M, Ekeland A, Moen CM, Aslaksen PM. Blame it on the weather? The association between pain in fibromyalgia, relative humidity, temperature and barometric pressure. PLoS One 2019;14:e0216902.

[19] Feinglass J, Lee J, Semanik P, Song J, Dunlop D, Chang R. The effects of daily weather on accelerometer-measured physical activity. J Phys Act Heal 2011;8:934–43.

[20] Ferreira ML, Zhang Y, Metcalf B, Makovey J, Bennell KL, March L, Hunter DJ. The influence of weather on the risk of pain exacerbation in patients with knee osteoarthritis – a case-crossover study. Osteoarthr Cartil 2016;24:2042–7.

[21] de Figueiredo ECQ, Figueiredo GC, Dantas RT. Influence of meteorological elements on osteoarthritis pain: a review of the literature. Rev Bras Reumatol 2011;51:616–28.

[22] de Figueiredo ECQ, Figueiredo GC, Targino Dantas R, Queiroga De Figueiredo EC, Dantas RT. Influence of weather on osteoarthritis of the hands. Curr Orthop Pract 2013;24:171–8.

[23] Fors EA, Sexton H. Weather and the pain in fibromyalgia: are they related? Ann Rheum Dis 2002;61:247–50.

[24] Giske L, Sandvik L, Røe C. Comparison of daily and weekly retrospectively reported pain intensity in patients with localized and generalized musculoskeletal pain. Eur J Pain 2010;14:959–65.

[25] Glaser JA, Keffala V, Spratt K. Weather conditions and spinal patients. Spine J 2004;29:1369–73.

[26] Gorin AA, Smyth JM, Weisberg JN, Affleck G, Tennen H, Urrows S, Stone AA. Rheumatoid arthritis patients show weather sensitivity in daily life, but the relationship is not clinically significant. PAIN 1999;81:173–7.

[27] Greenland S. Multiple comparisons and association selection in general epidemiology. Int J Epidemiol 2008;37:430–4.

[28] Greenland S. Quantifying biases in causal models: classical confounding. Epidemiology 2003;14:300–6.

[29] Guedj D, Weinberger A. Effect of weather conditions on rheumatic patients. Ann Rheum Dis 1990;49:158–9.

[30] Hafström I, Hallengren M. Physiotherapy in subtropic climate improves functional capacity and health-related quality of life in Swedish patients with rheumatoid arthritis and spondylarthropathies still after 6 months. Scand J Rheumatol 2003;32:108–13.

[31] Hagglund KJ, Deuser WE, Buckelew SP, Hewett J, Kay DR. Weather, beliefs about weather, and disease severity among patients with fibromyalgia. Arthritis Rheum 1994;7:130–5.

[32] Harrel FE Jr. Regression modeling strategies—with applications to linear models, logistic and ordinal regression, and survival analysis. R Softw; 2015.

[33] Hawley DJ, Wolfe F, Lue FA, Moldofsky H. Seasonal symptom severity in patients with rheumatic diseases: a study of 1424 patients. J Rheumatol 2001;28:1900–9.

[34] Hernán MA, Robins JM. Causal Inference: What If. Boca Raton, FL: Chapman & Hall/CRC, 2020.

[35] Hollander JP, Yeostros SY, Hollander JP, Yeostros SY. The effect of simultaneous variations of humidity and barometric pressure on arthritis. AIBS Bull 1963;13:24–8.

[36] Höppe P, Martinac I. Indoor climate and air quality. Review of current and future topics in the field of ISB study group 10. Int J Biometeorol 1998;42:1–7.

[37] Iikuni N, Nakajima A, Inoue E, Tanaka E, Okamoto H, Hara M, Tomatsu T, Kamatani N, Yamanaka H. What's in season for rheumatoid arthritis patients? Seasonal fluctuations in disease activity. Rheumatology 2007;46:846–8.

[38] Işik M, Khan AS, Avşar Ü, Set T, Çayir Y. Climatic effect on rheumatoid arthritis. Turkiye Klin J Med Sci 2013;33:746–50.

[39] Jamison RN. Influence of weather on report of pain. Int Assoc Study Pain Newsl 1996;3–5.

[40] Jamison RN, Anderson KO, Slater MA. Weather changes and pain: perceived influence of local climate on pain complaint in chronic pain patients. PAIN 1995;61:309–15.

[41] Jena AB, Olenski AR, Molitor D, Miller N. Association between rainfall and diagnoses of joint or back pain: retrospective claims analysis. BMJ 2017;359:j5326.

[42] Jensen MP, Karoly P, Braver S. The measurement of clinical pain intensity: a comparison of six methods. PAIN 1986;27:117–26.

[43] Johansson M, Sullivan L. Influence of treatment and change of climate in women with rheumatoid arthritis. A controlled prospective study of psychological, medical and social effects. Scand J Rheumatol Suppl 1975;9:1–193.

[44] Koyama T, Nakao K, Takaishi J, Shibata M, Mashimo T, Yoshiya I. Changes in weather affect perception of pain in chronic pain patients. Pain Clin 1996;9:319–25.

[45] Laborde JM, Dando WA, Powers MJ. Influence of weather on osteoarthritics. Soc Sci Med 1986;23:549–54.

[46] Latman NS. Annual fluctuations in rheumatoid arthritis. J Rheumatol 1980;8:725–9.

[47] Leandro G. Meta-analysis in Medical Research: The handbook for the understanding and practice of meta-analysis. Oxford: BMJ Books, 2005. p. 15–21.

[48] Li WC, Zhang Y. Can the weather influence arthritis symptoms? Rheumatol Rep 2014;6:16–20.

[49] Macfarlane TV, McBeth J, Jones GT, Nicholl B, Macfarlane GJ. Whether the weather influences pain? Results from the EpiFunD study in north west England. Rheumatology 2010;49:1513–20.

[50] McAlindon T, Formica M, Schmid CH, Fletcher J. Changes in barometric pressure and ambient temperature influence osteoarthritis pain. Am J Med 2007;120:429–34.

[51] McGorry RW, Hsiang SM, Snook SH, Clancy EA, Young SL. Meteorological conditions and self-report of low back pain. Spine (Phila Pa 1976) 1998;23:2096–102.

[52] Neogi T, Chen C, Niu J, Chaisson C, Hunter DJ, Choi H, Zhang Y. Relation of temperature and humidity to the risk of recurrent gout attacks. Am J Epidemiol 2014;180:372–7.

[53] Patberg WR, Nienhuis RLF, Veringa F. Relation between meteorological factors and pain in rheumatoid arthritis in a marine climate. J Rheumatol 1985;12:711–15.

[54] Patberg WR, Rasker JJ. Weather effects in rheumatoid arthritis: from controversy to consensus. A Rev 2004;31:1327–34.

[55] Peek N, Rodrigues PP. Three controversies in health data science. Int J Data Sci Anal 2018;6:261–9.

[56] Peultier L, Lion A, Chary-Valckenaere I, Loeuille D, Zhang Z, Rat AC, Gueguen R, Paysant J, Perrin PP. Influence of meteorological elements on balance control and pain in patients with symptomatic knee osteoarthritis. Int J Biometeorol 2017;61:903–10.

[57] Pincus T, Miles C, Froud R, Underwood M, Carnes D, Taylor SJ. Methodological criteria for the assessment of moderators in systematic reviews of randomised controlled trials: a consensus study. BMC Med Res Methodol 2011;11:14.

[58] Redelmeier DA, Tversky A. On the belief that arthritis pain is related to the weather. Proc Natl Acad Sci U S A 1996;93:2895–6.
[59] Rentschler EB, Vanzant FR, Rowntree LG. Arthritic pain in relation to changes in weather. J Am Med Assoc 1929;92:1995–2000.
[60] Sato J. Weather change and pain: a behavioral animal study of the influences of simulated meteorological changes on chronic pain. Int J Biometeorol 2003;92:1995–2000.
[61] Savage EM, McCormick D, McDonald S, Moore O, Stevenson M, Cairns AP. Does rheumatoid arthritis disease activity correlate with weather conditions? Rheumatol Int 2015;35:887–90.
[62] Schuh A, Senn E. Climate und Rheumatic Diseases. Rheumatic Diseases and Sport. Rheumatology. Vol. 16. Basel: Karcher, 1992. p. 22–39.
[63] Sibley JT. Weather and arthritis symptoms. J Rheumatol 1985;12: 707–10.
[64] Smedslund G, Eide H, Kristjansdottir ÓB, Nes AAG, Sexton H, Fors EA. Do weather changes influence pain levels in women with fibromyalgia, and can psychosocial variables moderate these influences? Int J Biometeorol 2014;58:1451–7.
[65] Smedslund G, Hagen KBKB. Does rain really cause pain? A systematic review of the associations between weather factors and severity of pain in people with rheumatoid arthritis. Eur J Pain 2011;15:5–10.
[66] Smedslund G, Mowinckel P, Heiberg T, Kvien TK, Hagen KB. Does the weather really matter? A cohort study of influences of weather and solar conditions on daily variations of joint pain in patients with rheumatoid arthritis. Arthritis Rheum 2009;61:1243–7.
[67] Smith G. Step away from stepwise. J Big Data 2018:32.
[68] Steffens D, Maher CG, Li Q, Ferreira ML, Pereira LSM, Koes BW, Latimer J. Effect of weather on back pain: results from a case-crossover study. Arthritis Care Res 2014;66:1867–72.
[69] Strusberg I, Mendelberg RC, Serra HA, Strusberg AM. Influence of weather conditions on rheumatic pain. J Rheumatol 2002;29:335–8.
[70] Timmermans EJ, van der Pas S, Schaap LA, Sanchez-Martinez M, Zambon S, Peter R, Pedersen NL, Dennison EM, Denkinger M, Castell MV, Siviero P, Herbolsheimer F, Edwards MH, Otero A, Deeg DJ. Self-perceived weather sensitivity and joint pain in older people with osteoarthritis in six European countries: results from the European Project on OSteoArthritis (EPOSA). BMC Musculoskelet Disord 2014;15: 66.
[71] Timmermans EJ, Schaap LA, Herbolsheimer F, Dennison EM, Maggi S, Pedersen NL, Castell MV, Denkinger MD, Edwards MH, Limongi F, Sanchez-Martinez M, Siviero P, Queipo R, Peter R, van der Pas S, Deeg DJ, Group ER. The influence of weather conditions on joint pain in older people with osteoarthritis: results from the European Project on OSteoArthritis. J Rheumatol 2015;42:1885–92.
[72] Tsai WS, Yang YH, Wang LC, Chiang BL. Abrupt temperature change triggers arthralgia in patients with juvenile rheumatoid arthritis. J Microbiol Immunol Infect 2006;39:465–70.
[73] Vergés J, Montell E, Tomàs E, Cumelles G, Castañeda G, Marti N, Möller I. Weather conditions can influence rheumatic diseases. Proc West Pharmacol Soc 2004;47:134–6.
[74] Viitanen J, Kautiainen H, Isomaki H. Changes in atmospheric pressure do not influence the pain of patients with primary fibromyalgia. J Musculoskelet Pain 1995;3:77–82.
[75] Vittinghoff E, Glidden DV, Shiboski SC, McCulloch CE. Predictor selection. Regression methods in biostatistics: linear, logistic, survival, and repeated measures models. New York: Springer Science & Business Media, 2011. p. 395–429.
[76] Vittinghoff E, Shiboski SC, Glidden DV, McCulloch CE. Strengthening causal inference. Regression methods in biostatitics: linear, logistic, survival, and repeated measures models. New York: Springer Science & Business Media, 2011. p. 331–94.
[77] Wilder FV, Hall BJ, Barrett JP. Osteoarthritis pain and weather. Rheumatology 2003;42:955–8.
[78] Wingstrand H, Wingstrand A, Krantz P. Intracapsular and atmospheric pressure in the dynamics and stability of the hip: a biomechanical study. Acta orthopaedica Scandinavica 1990: 231–35.