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Building narratives to characterise uncertainty in regional climate change through expert elicitation

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Abstract

Knowledge about regional and local climate change can inform climate risk assessments and adaptation decisions. However, estimates of future precipitation change at the regional and local level are deeply uncertain for many parts of the world. A novel methodology was developed that uses climate processes and expert elicitation to build narratives of future regional precipitation change. The narratives qualitatively describe physically plausible evolutions of future regional climate substantiated by climate processes. This method is applied to the Indian Summer Monsoon, focusing on the Cauvery River Basin in Karnataka, Southern India. Six climate narratives are constructed as a function of two drivers prioritised by the experts: moisture availability over the Arabian Sea and strength of the low-level westerly flow. The narratives describe how future precipitation could change until the 2050s and which climate processes and anthropogenic factors could influence this evolution. Analysis using observed (Global Precipitation Climatology Centre) and re-analysis (ERA20 and Interim) data shows the experts' judgement on key drivers fits well with empirical relationships. The expert elicited drivers explain 70% of the variance in peak monsoon precipitation (July and August) over the Western Ghats between 1979–2013 (using ERA Interim). The study shows that through expert elicitation, process-based narratives enable climate scientists to characterise and communicate elements of deep uncertainty in future precipitation change. Expert judgment techniques need be more widely applied to characterise uncertainty in regional and local climate change.

1. Introduction

Knowledge about regional and local climate change can inform climate risk assessments and adaptation decisions (Field *et al* 2014). Most regional scale climate information about the future is derived from general circulation models or downstream applications such as statistical or dynamical downscaling (e.g. regional climate models) and bias correction. This is done despite a widespread acknowledgment that in many parts of the world these types of models have considerable limitations in representing important present-day climatic processes (Knutti and Sedlacek 2013, Shepherd 2014), especially monsoons (Wang *et al* 2017). Climate model projections of variables such as precipitation vary considerably and non-independent errors due to shared assumptions and implementations indicate that the full range of uncertainty may not be sampled.

Precipitation at a location is one of the most sought after variables in applying regional climate change projections, and yet it is one of the most uncertain

(Risbey and O'Kane 2011). Various types of errors and uncertainties make climate model output of future regional precipitation difficult to interpret (Stainforth *et al* 2007). These difficulties are not resolved by the use of model ensembles, model weighting or downscaling (Risbey and O'Kane 2011). Understanding the quality of the knowledge about regional climate change is important because it serves as an input to climate risk assessments which inform decisions about adaptation to a changing climate across society (Bhave *et al* 2018 provides a relevant example in water resources planning for the Cauvery River Basin in Karnataka).

Alternative approaches to representing uncertainty in climate change are emerging. Hazeleger *et al* (2015) have proposed the development of 'tales of future weather' through the use of numerical weather prediction models in a hypothetical climate setting. James *et al* (2015) undertook a process-based assessment of climate projections using historical years in models and reanalyses for West Africa. Zappa and Shepherd (2017) constructed storylines of atmospheric circulation change for the Euro-Atlantic region using CMIP5 climate model simulations. To quantify plausible bounds of the Earth's equilibrium climate sensitivity, Stevens *et al* (2016) developed and refuted physical storylines of low and high climate sensitivities using expert judgment.

Expert judgment techniques have been used in climate change research to estimate climate sensitivity (Morgan and Keith 1995), future sea level rise (Bamber and Aspinall 2013) and tipping points in the climate system (Kriegler *et al* 2009). However, the application of expert elicitation to regional climate change has largely been undocumented, underspecified or incipient with a few exceptions (Mearns *et al* 2017, Risbey *et al* 2002). Given the large uncertainties in projecting regional and local climate change, Thompson *et al* (2016) have argued that subjective expert judgment should play a central role in the provision of such information to support adaptation planning and decision-making.

Here, we develop a novel methodology that uses structured expert elicitation to identify key processes controlling and influencing regional climate to build climate narratives: qualitative physical descriptions of plausible future evolutions of regional climate (section 3). We assess the influence of drivers underlying the expert-derived climate narratives on regional climate using observed and reanalysis data (section 4) and discuss our findings (section 5). We test this new approach for the Indian Summer Monsoon with a focus on the Cauvery river basin in Karnataka, Southern India, which is introduced next.

2. Study region

The Cauvery river (~800 km) is an important river of southern India, flowing eastwards from the Western Ghats into the Bay of Bengal (Vanham *et al* 2011). The study region encompasses the Cauvery river basin in Karnataka (CRBK; 35 960 km^2) (figure 1(*a*)). CRBK's western ridge comprises an important physiographical feature: the Western Ghats mountain ranges. These ranges run along India's western coast forming a north-south barrier to the south-westerly advance of the Indian Summer Monsoon (ISM) and cause heavy orographic precipitation (figure 1). Most precipitation occurs between mid-June and mid-September when the Westerly (Somali) Jet brings moisture from over the Arabian Sea (Levine and Turner 2012). A steep precipitation gradient is observed in this period on the leeward side (into the CRBK) because of the rain-shadow effect, which can be as high as 100 mm km^{-1} for a 10 km stretch (Gunnell 1997). As a result, central and eastern CRBK (excluding Western Ghats) is relatively dry and drought prone (figures 1(*b*) and (*c*)). Over the 1901–2013 period, a weak and insignificant decreasing trend is observed in the Western Ghats (figure 1(*d*)). However, a significant ($p < 0.1$) decreasing trend has been observed for the period 1971–2004 in the Western Ghats based on the $1° \times 1°$ Indian Meteorological Department data (not shown; Ministry of Water Resources 2014). The CRBK is an important basin because it provides water for irrigation (~6000 km^2); domestic water supply (through pumping) to Bangalore (population ~10 million) the financial and administrative capital of Karnataka; environmental requirements; and downstream riparian states (Vanham *et al* 2011).

Climate model output over the Cauvery river basin has been used to infer potential future precipitation change in the basin. Bhuvaneswari *et al* (2013) found, for an ensemble of 16 different General Circulation Models (GCMs) under the A1B emission scenario, projections of higher precipitation in the CRBK (inter-model range 1%–36%) by the 2050s, compared to a baseline (1981–2000). Using one regional climate model driven by one GCM under three representative concentration pathways (RCPs), Pechlivanidis *et al* (2016) obtained increases in precipitation in the Cauvery by mid-century (2021–2050, with baseline 1976–2005) under all RCPs. In contrast, India's second national communication to the United Nations Framework Convention on Climate Change reports a marginal decrease in precipitation in the Cauvery in 2021–50 compared to 1961–90 using outputs from the PRECIS regional climate model for A1B emission scenario (Ministry of Environment and Forests 2012). The Karnataka Climate Change Action Plan used PRECIS outputs to derive district level projections alongside projections from multiple GCMs. Based on 21 GCMs, the report presents an inter-model range of ±~17% change in precipitation for Karnataka for 2021–2050 compared to 1961–1990 (BCCI-K 2011). In summary, the results for the Cauvery river and the state of Karnataka encompass a wide range of future precipitation outcomes, and whilst there is a tendency

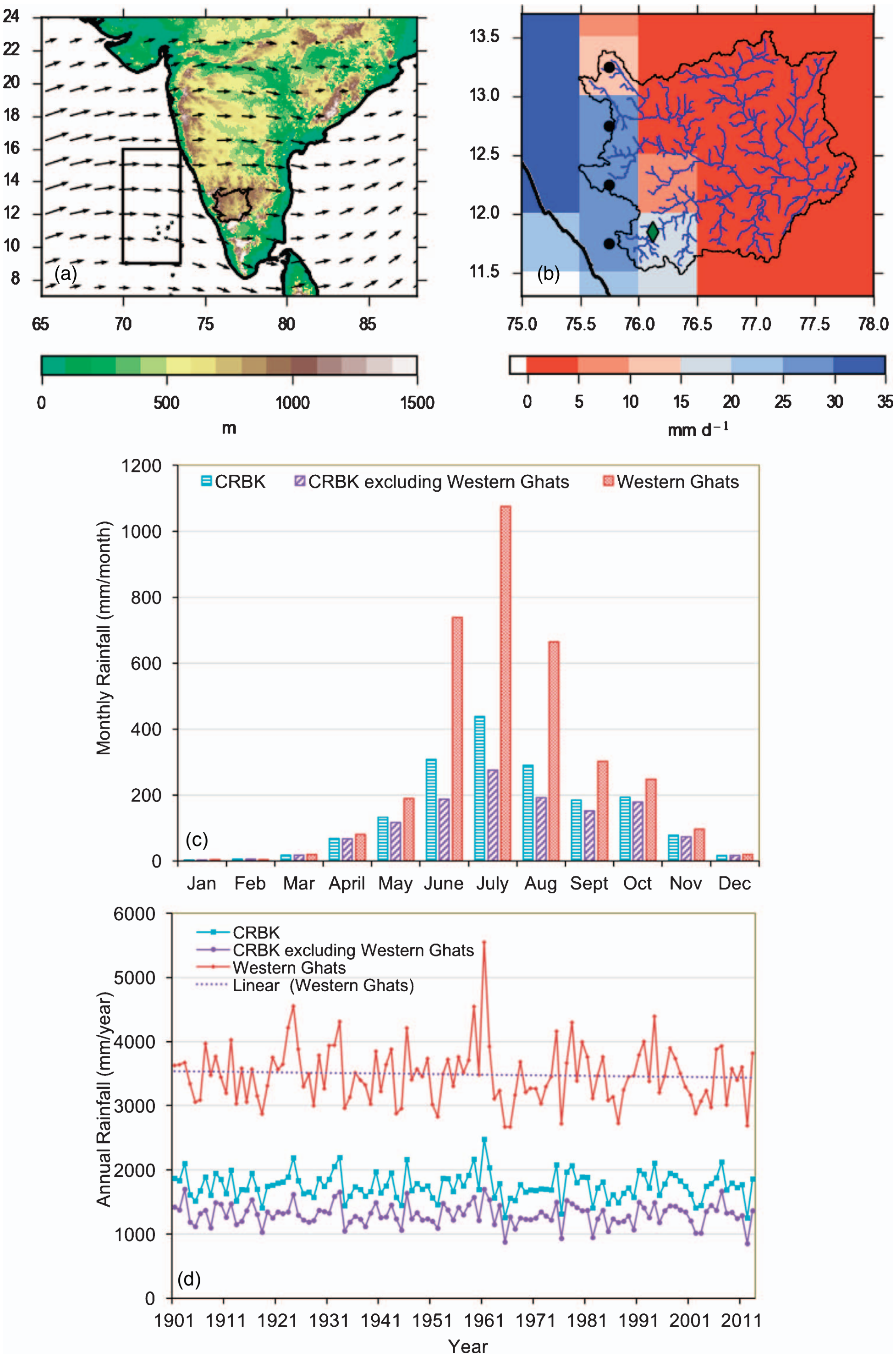


Figure 1. Catchment location and topography; grids evaluated for precipitation along the Western Ghats and moisture flux in the Arabian Sea; and climatological context of the catchment. (*a*) Topography height (m), the location of the Cauvery river basin in Karnataka (CRBK; black outline), ERA-Interim 900 hPa (approx. 1000 m above surface) wind averaged over peak southwest monsoon months of July and August 1979–2013 (vectors) and the moisture flux averaging area (black box). (*b*) The mean July and August GPCC (Global Precipitation Climatology Centre) precipitation averaged over July and August 1979–2013 (shading) and river network (blue lines). Black dots indicate grid boxes chosen to extract observed precipitation for the Western Ghats within the CRBK; the streamflow gauging station at Muthankera is also indicated (green diamond). (*c*) GPCC area-averaged monthly precipitation over the period 1979–2013 for the CRBK, with its two sub-regions: the Western Ghats mountain ranges, and the CRBK excluding the Western Ghats. (*d*) GPCC area-averaged annual precipitation for the period 1901–2013 for the CRBK, with its two sub-regions: the Western Ghats mountain ranges (including a linear trend) and the CRBK excluding the Western Ghats.

towards higher precipitation, some models project much drier conditions. No studies present systematic information about the nature and extent of uncertainty associated with future precipitation projections (cf. Risbey and O'Kane 2011, Thompson *et al* 2016).

3. Climate processes, expert elicitation and climate narratives

We conducted an expert elicitation workshop with eight experts in the ISM to capture knowledge on how the precipitation in Southern India could evolve between now and the 2050s (supplementary information 1 available at stacks.iop.org/ERL/13/074005/mmedia provides more details about the workshop including duration, expert recruitment and experts' area of expertise). The workshop was structured using the qualitative parts of the Sheffield elicitation framework (SHELF) protocol (Oakley and O'Hagan 2016) that aims to minimise biases in judgements made by experts and maximise information sharing (as described in O'Hagan *et al* 2006). Experience in conducting expert knowledge elicitation using SHELF has concluded that having five-to-ten experts is practicable (Gosling 2018). To enable experts to give judgements and share information, the workshop was operated under the Chatham House rule and the facilitator gave frequent opportunities for all the experts to participate equally irrespective of perceived seniority.

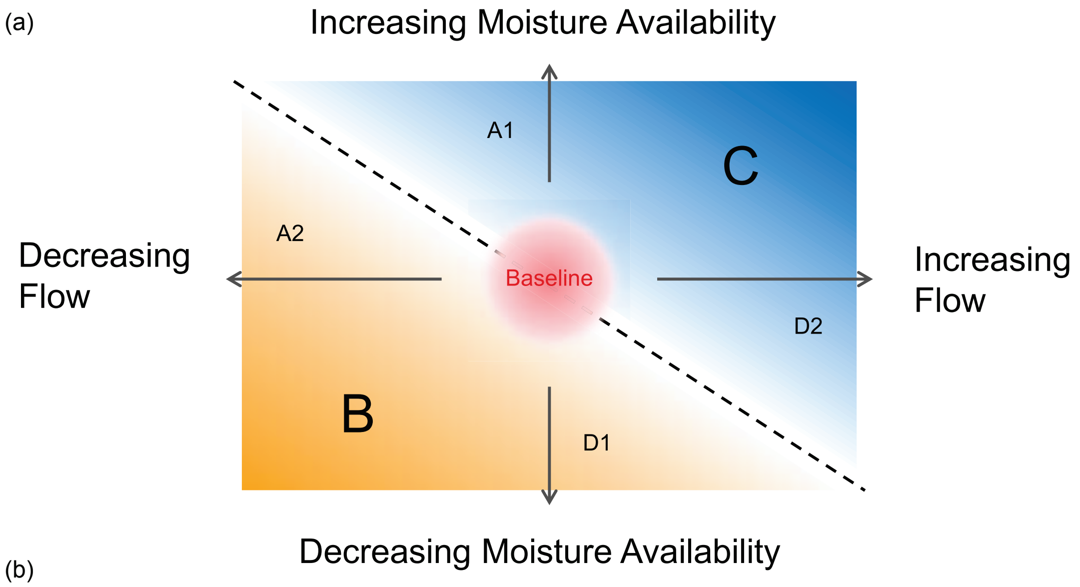
The lead author, with support from four co-authors, facilitated the workshop, beginning with an explanation of the workshop's purpose, rationale, focus region, and water resources decision context in the CRBK. The experts then introduced themselves and described their expertise and experience, followed by an expert-led discussion on missing expertise. Hydrology and oceanography were considered important areas of missing expertise, but not critical to the workshop objectives. We then initiated a discussion amongst the experts to identify key climate processes which influence the ISM precipitation. Initially, 23 climatic processes controlling and influencing ISM precipitation were identified by the experts (supplementary information 2). The experts then clustered the 23 processes according to the time scale of influence: synoptic/weather, intra-seasonal, inter-annual, decadal and long term.

As a shared understanding of complex interactions emerged, we discussed how to narrow down the processes to the two most important ones in order to define narrative axes (cf. scenario-axes technique in van't Klooster and van Asselt 2006) and relevant descriptors. Experts debated different options for the axes and eliminated them based on various criteria. For instance, global temperature rise was eliminated because it is not significantly different for different RCPs till 2050 (the time frame for the narratives). Processes such as aerosol forcing, land use change, and land-sea temperature contrast, were considered inter-dependent and therefore could not characterize one axis.

A consensus emerged that both axes should encompass multiple climate processes, to enable a process-based description of each narrative. By narrowing the focus from Southern India to the CRBK, experts agreed that the most important driver of ISM precipitation was the flow of moisture over the Western Ghats. This flow could be decomposed into moisture availability over the Arabian Sea (amount of moisture available in the air column) and strength of flow perpendicular to the Western Ghats (figure 2(*a*)). A discussion followed on the sensitivity of precipitation to these two drivers and the plausibility of an increase/decrease in both axes. Experts agreed that all four quadrants are plausible (although not necessarily equally likely; e.g. experts considered a decrease in moisture availability plausible but unlikely). We captured the experts' descriptions of each narrative at the workshop based on consolidation of detailed notes made by the five co-authors present.

Narrative descriptions were characterized by their potential evolution and implications for plausible future precipitation change (box 1 and figure 2). The experts agreed on the sign of mean precipitation change expected for each narrative, but highlighted the potential importance of uncertainties in precipitation variability, rate of precipitation change, changes in precipitation extremes, timing of onset of ISM, and active/break cycles. Experts agreed that increasing moisture availability and increasing flow into the Western Ghats (Narrative C) would increase precipitation, while a decrease in both (Narrative B) would reduce precipitation. For Narratives A and D, precipitation could either increase or decrease depending on the relative dominance of the two key drivers. Therefore narratives A1, A2, D1 and D2 were developed, based on the dominance of one of the drivers. After the workshop, a description of the climate narratives was circulated to the group of experts to check if it represented the consensus reached at the workshop; only very minor revisions were necessary. Box 1 shows the elicited climate narratives.

Experts prioritised ten climatic processes, whose future evolution could play an important role in the development of the narratives (figure 2(*b*) and box 1). These processes consisted of natural climatic processes (e.g. Inter Tropical Convergence Zone (ITCZ) movement northwards) and anthropogenic factors (e.g. extent of irrigation) (see supplementary information 3). For example, under Narrative B, both moisture availability and strength of flow would decrease (compared to the baseline) leading to an expected reduction in precipitation. For this to occur, underlying plausible processes could include: weakening of the Westerly Jet which would decrease the strength of flow (Joseph and Sijikumar 2004, Sandeep and Ajayamohan 2015); increase in anthropogenic aerosol forcing which



(b)

Narrative	Key Processes									Precipitation Change
	Arabian Sea/ Indian Ocean SST	Atmospheric Moisture	Horizontal Tropospheric Temperature Gradient	Himalayan Snow Cover	Anthropogenic Aerosol Forcing	ITCZ movement northwards	Strength of Westerly Jet	Extent of irrigation	Influence of dry Northerlies	Influential Tele - connections	
A1	⇧	⇧	⇧	⇩	⇩	⇧	⇧	⇩	⇩	La Niña	↑
A2	⇧		⇩	⇧	⇧	⇩	⇩	⇧	⇧	El Niño EQUINOO	↓
B	⇩		⇩	⇧	⇧	⇩	⇩	⇧	⇧	El Niño EQUINOO	⬇
C	⇧	⇧	⇧	⇩	⇩	⇧	⇧	⇩	⇩	La Niña	⬆
D1	⇩		⇩	⇧	⇧	⇩	⇩	⇧	⇧	El Niño EQUINOO	↓
D2	⇩	⇧	⇧	⇩	⇩	⇧	⇧	⇩	⇩	La Niña	↑

Figure 2. Elicited climate narratives for the CRBK, associated changes in key processes and precipitation. (*a*) Expert elicited climate narratives for the Cauvery River Basin in Karnataka for the 2050s as a function of two climate drivers: moisture availability over the Arabian Sea (*y*-axis) and strength of flow perpendicular to the Western Ghats (*x*-axis). The red circle in the centre indicates current baseline conditions. The black dashed line divides the narratives into two areas where the experts expected precipitation to increase (blue areas covering narratives C, A1 and D2) and decrease (yellow areas covering narratives B, A2 and D1). (*b*) Expert elicited key processes governing the Indian Summer Monsoon, including their expected future direction of change (increase, decrease or no change) for each climate narrative and expected precipitation change (includes large and small changes). More information on these processes is available in supplementary information 3. Acronyms: SST—Sea Surface Temperature; ITCZ—Inter Tropical Convergence Zone; EQUINOO—Equatorial Indian Ocean Oscillation.

reduces the land-sea temperature contrast and changes the cloud microphysics, which suppresses precipitation (Bollasina *et al* 2011, Krishnan *et al* 2016); increase in irrigation in the Indo-Gangetic Plain which reduces the land-sea temperature contrast and decreases overall monsoon circulation (Saeed *et al* 2009, Niyogi *et al* 2010); greater influence of the El Niño (Cherchi and Navarra 2013, Roy *et al* 2017) and Equatorial Indian Ocean Oscillation (Sajani *et al* 2015) teleconnections; and the cooling of sea surface temperatures which would reduce available moisture (we found no relevant published literature about this process and some experts expressed scepticism of its likelihood).

4. Climate analysis

We assessed the relative importance of the expert derived drivers in influencing precipitation and streamflow in the study region using climate observations and re-analysis data. We used proxies for the two expert-elicited axes: specific humidity over the Arabian Sea

Box 1. Description of expert elicited climate narratives for study region.

Narrative A describes future evolution of the ISM for increasing moisture availability and decreasing strength of flow coming towards southern India. Their relative dominance will determine the amount of precipitation, leading to two sets of conditions affecting precipitation:

A1: If the increase of moisture availability prevails over the decrease in flow strength, precipitation is expected to increase compared to the present day while impacts on inter-annual variability are uncertain. For this to occur, underlying plausible processes could include increase in sea surface temperatures in the Arabian Sea and Indian Ocean, weaker influence of dry northerlies and reduction of anthropogenic aerosol forcing.

A2: If the decrease of flow strength prevails over the reduction in moisture, precipitation is expected to decrease compared to the present day. For this to occur, underlying plausible processes could include increased anthropogenic aerosol forcing in the northern hemisphere (particularly in northern India) and warming of the Arabian Sea and Indian Ocean resulting in the weakening of the tropospheric temperature gradient.

Narrative B describes future evolution of the ISM for decreasing moisture availability and decreasing strength of flow coming towards southern India. Under these conditions, precipitation is expected to decrease due to the underlying plausible processes of cooling of sea surface temperatures of the Arabian Sea, weakening of the Westerly Jet, increase in anthropogenic aerosol forcing in the northern hemisphere (particularly in northern India), increase in irrigation in the Indo-Gangetic Plain which cools the land surface and decreases overall monsoon circulation, and greater influence of the El Niño and Equatorial Indian Ocean Oscillation teleconnections. Land use change and its effect on soil moisture content and evapotranspiration are expected to impact the spatio-temporal distribution of precipitation, which, although uncertain, is expected to be different compared to current conditions.

Narrative C describes future evolution of the ISM for increasing moisture availability and increasing strength of flow coming towards southern India. Under these conditions, precipitation is expected to increase due to underlying plausible processes of global atmospheric moisture increase and intensification of the tropospheric temperature gradient, greater northward shift of the Inter Tropical Convergence Zone and greater influence of the La Niña teleconnection. Precipitation is expected to increase in a non-linear manner, while impacts on interannual variability, spatial distribution of precipitation and effects of orography are uncertain.

Narrative D describes future evolution of the ISM for decreasing moisture availability and increasing strength of flow coming towards southern India. Their relative dominance will determine the amount of precipitation leading to two sets of conditions:

D.1: If the reduction in moisture availability prevails over the increase in flow strength, precipitation is expected to reduce compared to the present day. For this to occur, underlying plausible processes could include cooling of sea surface temperatures in the Arabian Sea and Indian Ocean, greater influence of dry northerlies and greater anthropogenic aerosol forcing.

D.2: If the increase of flow strength prevails over the reduction in moisture availability, precipitation is expected to increase compared to the present day. For this to occur, underlying plausible processes could include global atmospheric moisture increase and reduction in Himalayan snow cover, leading to an intensification of the tropospheric temperature gradient.

for moisture availability and wind velocity for flow into the Western Ghats. Two reanalysis data products: ERA Interim (1979–2015; Dee *et al* 2011) and ERA 20 (1900–2010; Poli *et al* 2016) were used to extract specific humidity and the u (eastward) component of wind at nine pressure levels (800–1000 hPa). Means of specific humidity and u-wind were computed between 1000–800 hPa (from the surface to the average altitude of the Western Ghats; ~2000 m) over the box 70–73 °E, 9–16°N (figure 1(*a*)).

For analysing observed precipitation over the Western Ghats multiple datasets were considered. Given the continuous length of the data, its availability till recent years, and coverage of the region, the Global Precipitation Climatology Centre (GPCC) data (1901–2013; Becker *et al* 2013) was chosen for analysis of catchment precipitation. For comparing river streamflow with the moisture flux, data from the Muthankera stream gauge station (1973–2012; green diamond in figure 1(*b*)) was used because it has little human intervention, so it is the closest available record to a naturalised streamflow series.

While the ISM lasts from June (onset) to September (withdrawal), July and August are the peak ISM precipitation months over the Indian subcontinent, so the analysis focused on them. The relationship between moisture availability, zonal flow and precipitation was tested by computing anomalies relative to a 1981–2005 average of the yearly July–August averages (the baseline period). Figure 3 shows anomalies of specific humidity and zonal wind compared to the baseline period for ERA Interim (1979–2013) (figure 3 upper panel) and ERA20 (1901–2010) (figure 3 lower panel). The colour represents the corresponding observed precipitation anomaly over the ridge of the Western Ghats. Overall, there is a tendency for precipitation to

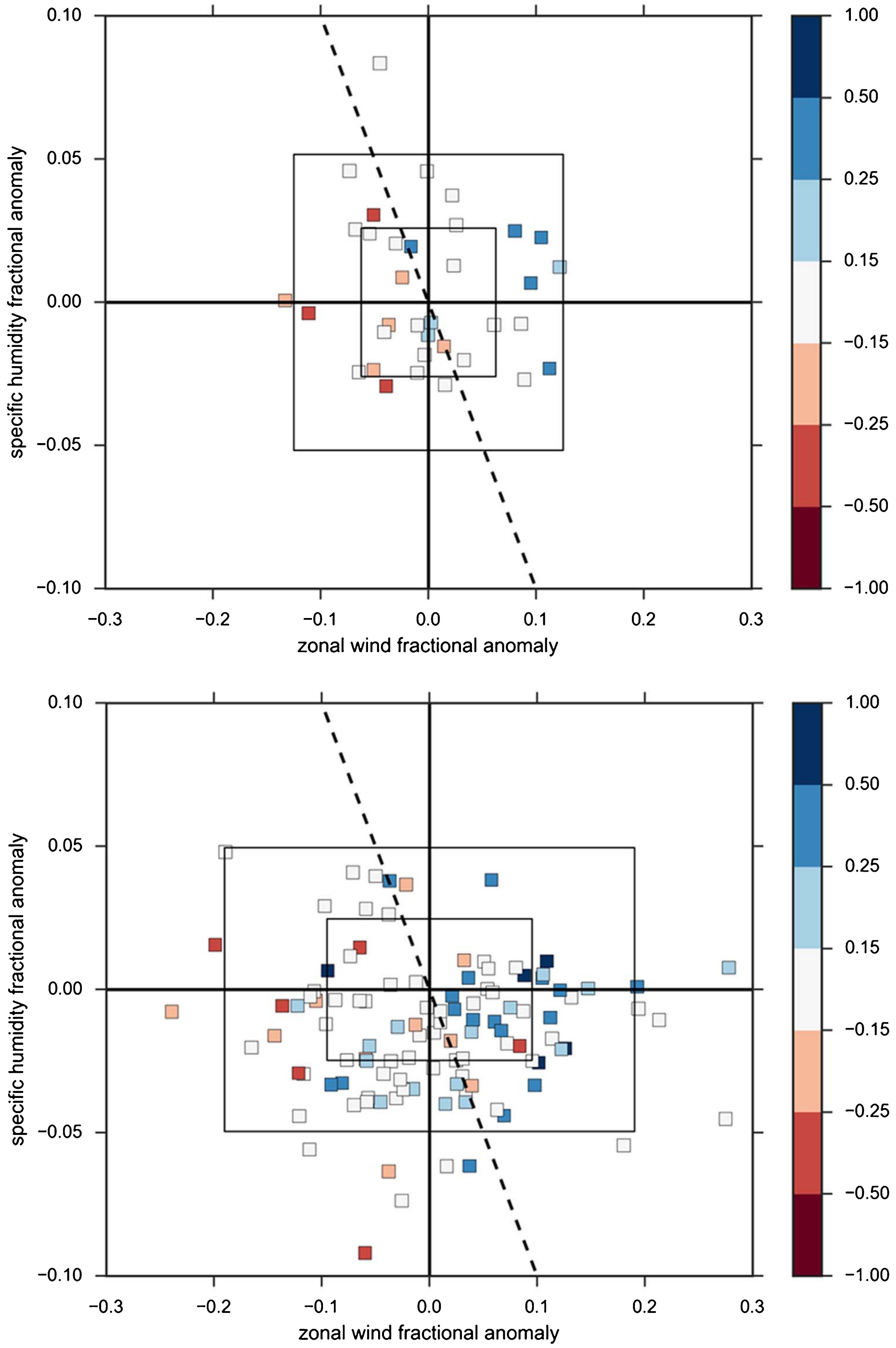


Figure 3. Changes in observed precipitation change and re-analysis moisture flux compared to a baseline period. Percentage anomaly of specific humidity and low-level zonal wind (1000–800 hPa) for peak southwest monsoon months of July and August over the Arabian Sea w.r.t. a 1981–2005 baseline for ERA Interim (1979–2013) (upper panel) and for ERA20 (1901–2010) (lower panel). Lined boxes represent 1σ and 2σ standard deviation. The colour represents the corresponding observed precipitation (GPCC) fractional anomaly over the ridge of the Western Ghats (calculated w.r.t. a 1981–2005 baseline).

increase with increasing flow and moisture availability, as one moves from the bottom-left quadrant to the top-right quadrant, as suggested during the expert elicitation. The 1:1 lines in figure 3 divide the plots into two halves; one with generally higher and one with generally lower precipitation than the baseline period. This is more visible in ERA Interim than in ERA20, potentially because ERA Interim assimilates many more observations (e.g. from satellites) than ERA20, which makes it closer to reality. The shorter length of ERA Interim could have also played a role in this difference. These results are consistent with the elicited expert judgments.

We further assessed the relationship between moisture flux (product of moisture availability over the

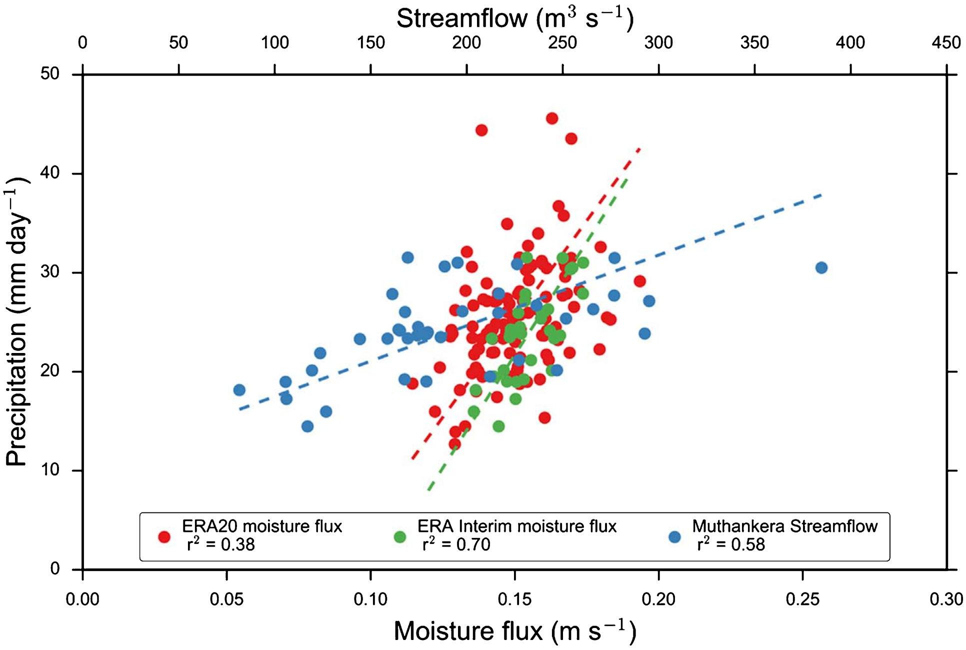


Figure 4. Relationship between peak southwest monsoon months of July and August moisture flux (product of surface humidity over the Arabian Sea and *u*-wind component) in reanalysis datasets—ERA20 (1901–2010), ERA Interim (1979–2013)—and corresponding observed precipitation (GPCC) over the ridge of the Western Ghats. Also shown is the relationship between observed precipitation and streamflow for July and August at Muthankera (green diamond in figure 1(*b*)).

Arabian Sea and flow perpendicular to the Western Ghats) and observed precipitation over the Western Ghats (figure 4). Correlation coefficients and total least-squares regression lines were computed using all overlapping years for (i) moisture flux and precipitation, (ii) precipitation and streamflow, and (iii) moisture flux and streamflow to determine the statistical significance of the linear relationships. We chose total least squares regression because it minimises the sum of squared residuals in both x and y directions, and so considers potential observational errors in both the dependent and independent variables. For all three quantities, the percentage changes relative to this baseline were used.

Statistically significant relationships ($p < 0.01$) were found with ERA Interim moisture flux ($R^2 = 0.70$) being more strongly related than ERA 20 moisture flux ($R^2 = 0.38$) with observed precipitation (figure 4). The gradients of ERA Interim and ERA20 are almost the same, showing good consistency. These regression lines can be used to translate the qualitative narratives into illustrative quantitative time series of precipitation change which are useful for quantitative climate impact and adaptation assessments (see supplementary information 4). A reasonably strong relationship ($R^2 = 0.58$, $p < 0.01$) is also evident between observed precipitation in the ridge of the Western Ghats and streamflow at Muthankera gauging station in the Western Ghats (figure 4). There are natural hydrological processes (interception by vegetation, infiltration, evapotranspiration etc.) and there is low human interference upstream of this station, making it useful for assessing the direct relationship between moisture flux and observed streamflow. We found moderate relationships between moisture flux and observed streamflow at Muthankera using ERA Interim ($R^2 = 0.44$) and ERA 20 ($R^2 = 0.38$) (see supplementary information 5).

5. Discussion and conclusions

We have developed a new method to characterise and communicate uncertainty in regional climate change by building process-based narratives through structured expert elicitation. The method is flexible and relatively quick (e.g. compared with running new climate model simulations) so it can cater for the diverse and complex demands of the Vulnerability, Impacts, Adaptation and Climate Services (VIACS) community (cf. Hewitson *et al* 2014, Ruane *et al* 2016). In our application, we recruited both local and foreign climate scientists for the expert elicitation (in relation to the country where the case study was based). The lack of local climate experts in some parts of the world could raise issues of legitimacy if foreign participants dominate the expert elicitation in future applications.

The current practice of using climate models to develop regional climate projections for the Cauvery Basin either underestimates uncertainty by using a single global/regional climate model pair (Ministry of Environment and Forests 2012, Pechlivanidis *et al* 2016) or provides no guidance in interpreting multi-model ranges of uncertainty (Bhuvaneswari *et al* 2013, BCCI-K 2011). Such practice is widespread, leading to poor communication of uncertainty in regional climate change projections to the VIACS community that use these projections (cf. Risbey and O'Kane 2011). Thompson *et al* (2016) argue that for local climate change decision support, direct climate model outputs can be misleading. Our approach delivers a better characterisation of the sources of knowledge and uncertainty in regional climate change projections by: (1) having experts interpret climate model results, observations and theory, whilst developing process-based narratives; and (2) focusing on physically plausible evolutions of future regional climate, guided by understanding of climate processes.

In the case of the CRBK, this led experts to consider uncertainty spaces (e.g. decreases in moisture availability) which although deemed of low likelihood were nevertheless considered plausible and thus explored in the narratives. Using narratives to explore the boundaries of plausibility, enables us to go beyond the capabilities of current climate models, thereby guarding against false precision and surprise (Parker and Risbey 2015). The narrative approach and its results are not amenable to direct comparison with climate model based studies. This is because, although both are founded on physical processes, the former is focused on physical plausibility while the latter takes a reductionist approach resulting in a limited exploration of the uncertainty space.

Our research cross-checked the relationship between expert-elicited key drivers (moisture availability and strength of flow) and catchment precipitation using observations and re-analysis data. This climate analysis made two important contributions: (1) the good agreement between the expert elicited judgments underlying the narratives and the empirical relationships in the observational and reanalysis data gives confidence in the method developed and supports its wider application; (2) the empirical relationships between moisture flux and observed precipitation enable the translation of qualitative narratives into illustrative quantitative time series of precipitation change which can serve as input to climate impact models (see supplementary information 4 and Bhave *et al* 2018).

Our approach is one of several expert judgment techniques. The appropriateness of different techniques will depend on the regional context being studied. For example, continental scale temperature changes in the next 30 years may be amenable to quantitative elicitation techniques (that elicit probability density functions, bounds or expected signs) whereas local precipitation changes by the end of the century may not be suitable for such quantitative approaches (Risbey and O'Kane 2011). There is no one-size-fits-all approach to representing uncertainty; the level of precision in reporting uncertainty needs to match scientists' belief about the extent to which there is uncertainty, which depending on the context could range from precise Bayesian probabilities to effective ignorance (Kandlikar *et al* 2005, Parker and Risbey 2015).

Climate process-based expert elicitation and narratives have an important role to play in informing regional and local risk assessments and adaptation decisions when future climate uncertainty is large. Bhave *et al* (2018) have, for example, used qualitative narratives and associated quantitative time series of precipitation change to examine long-term water resources planning in the CRBK. Expert judgment techniques need to be more widely applied to characterise uncertainty in regional and local climate change.

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