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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 rainfall 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 rainfall 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 climate processes and anthropogenic factors could influence their potential 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 rainfall (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 deep uncertainty in future rainfall change. Expert judgment techniques should be more widely applied to characterise uncertainty in regional and local climate change.

Keywords: regional climate change; uncertainty; climate processes; narratives; expert elicitation; Indian Summer Monsoon; Cauvery

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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 rainfall vary considerably and non-independent errors due to shared assumptions and implementations indicate that the full range of uncertainty may not be sampled.

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) undertake a process-based assessment of climate projections using historical years in models and reanalyses for West Africa. Zappa & 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; 35,960km^2) (Figure 1a). 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 with July and August being peak monsoon months when the Westerly (Somali) Jet brings moisture from over the Arabian Sea (Levine and Turner, 2012). A steep precipitation gradient is observed towards the leeward side (into the CRBK) because of the rain-shadow effect, which can be as high as 100mm/km for a 10 km stretch (Gunnell, 1997). As a result, central and eastern CRBK is relatively dry and drought prone (Figure 1b). 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; for environmental requirements; and for downstream riparian states (Vanham et al., 2011).

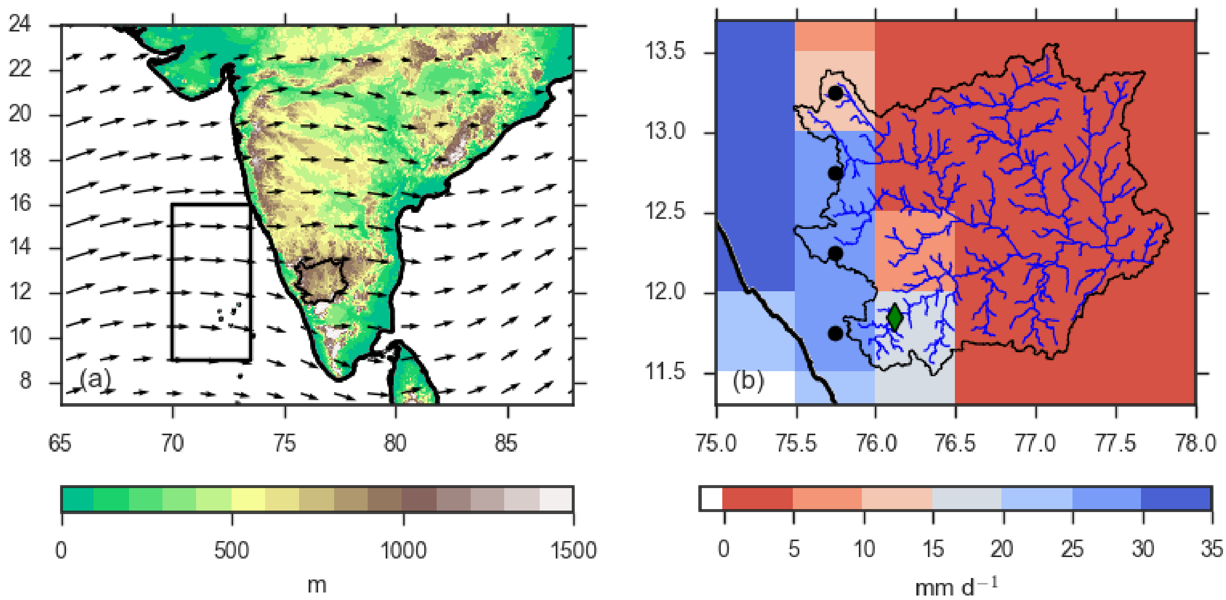


Figure 1: **Catchment location and topography, and grids evaluated for precipitation along the Western Ghats and moisture flux in the Arabian Sea**.
(a) Topography height (m), the location of the Cauvery river basin in Karnataka (black outline), ERA-Interim 900hPa (approx. 1000m above surface) wind averaged over peak southwest monsoon months of July and August 1979-2013 (vectors) and the moisture flux averaging area (black box) and (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)

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 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.

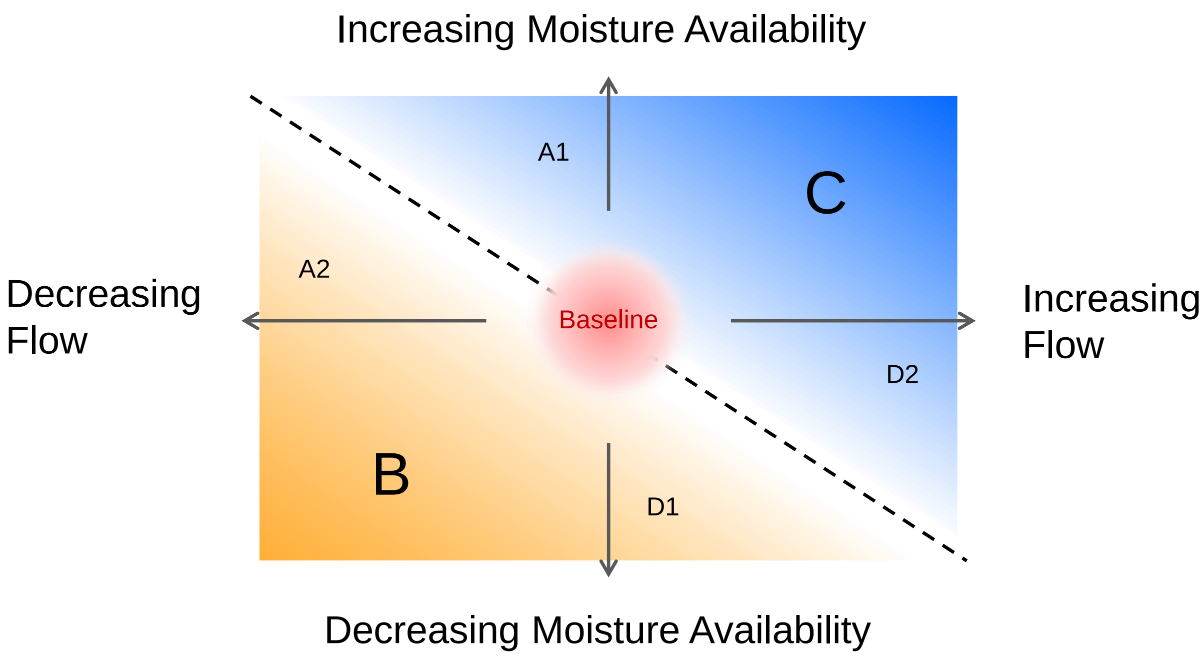
As a shared understanding of complex interactions emerged, we discussed how to narrow down the processes to the two most important ones in order to define narrative axes (cf. scenario-axes technique in van 't Klooster and van Asselt, 2006) and relevant descriptors. Experts debated different options for 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 rainfall 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 2a). 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 10 climatic processes, whose future evolution could play an important role in the development of the narratives (Figure 2b 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 rainfall. 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 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 and some experts expressed scepticism of its likelihood).



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.

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 for moisture availability and wind velocity for flow into the Western Ghats (Figure 1a). Mean specific humidity between 1000-800 hPa (from the surface to the average altitude of the Western Ghats; ~2000m) was computed over the box 70-73 °E, 9-16°N (Figure 1a). 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 at 9 pressure levels (800-1000hPa). The mean u-wind (eastward) component was computed for the same heights and area as the specific humidity.

For analysing observed rainfall over the Western Ghats multiple datasets were tested. Considering the continuous length of the data, availability till recent years, and coverage of the region, Global Precipitation Climatology Centre (GPCC) precipitation data (1901-2013; Becker et al., 2013) was used for analysis of catchment rainfall. For comparing river streamflow with the moisture flux, data from the Muthankera stream gauge station (1973-2012) was used because it has little human intervention, so it's the closest to a naturalised flow series.

While the ISM lasts from June (onset) to September (withdrawal), July and August are the peak ISM precipitation months 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. 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 increase with increasing flow and moisture availability, as one moves from the bottom-left quadrant to the top-right quadrant. The 1:1 lines in Figure 3 divide the plot 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. These results are consistent with the elicited expert judgments.

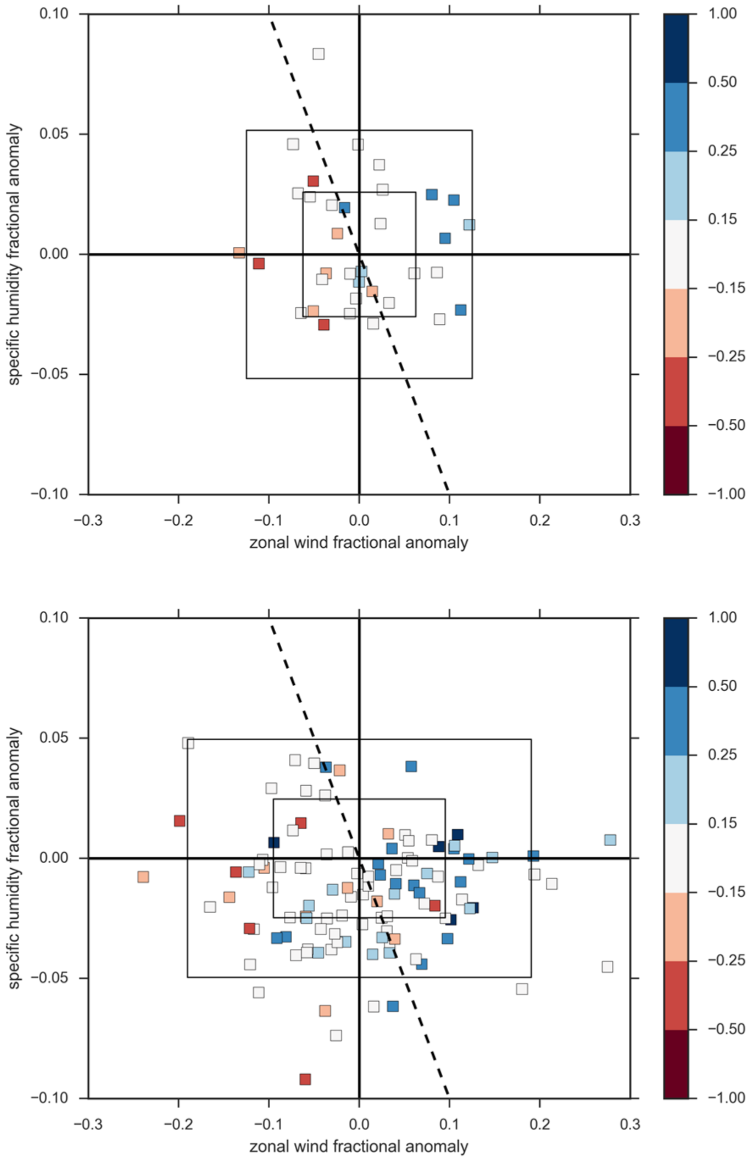


Figure 3: Changes in observed precipitation change and re-analysis moisture flux compared to a baseline period.
Percentage anomaly of specific humidity and low-level zonal wind (1000-800 hPa) for peak southwest monsoon months of July and August over the Arabian Sea w.r.t. a 1981-2005 baseline for ERA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

We further assessed the relationship between moisture flux (product of moisture availability over the Arabian Sea and flow perpendicular to the Western Ghats) and observed precipitation over the Western Ghats. 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. To test the significance of these relationships the moisture flux was first computed from the monthly specific humidity and eastward wind for each vertical level, before spatially averaging.

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).

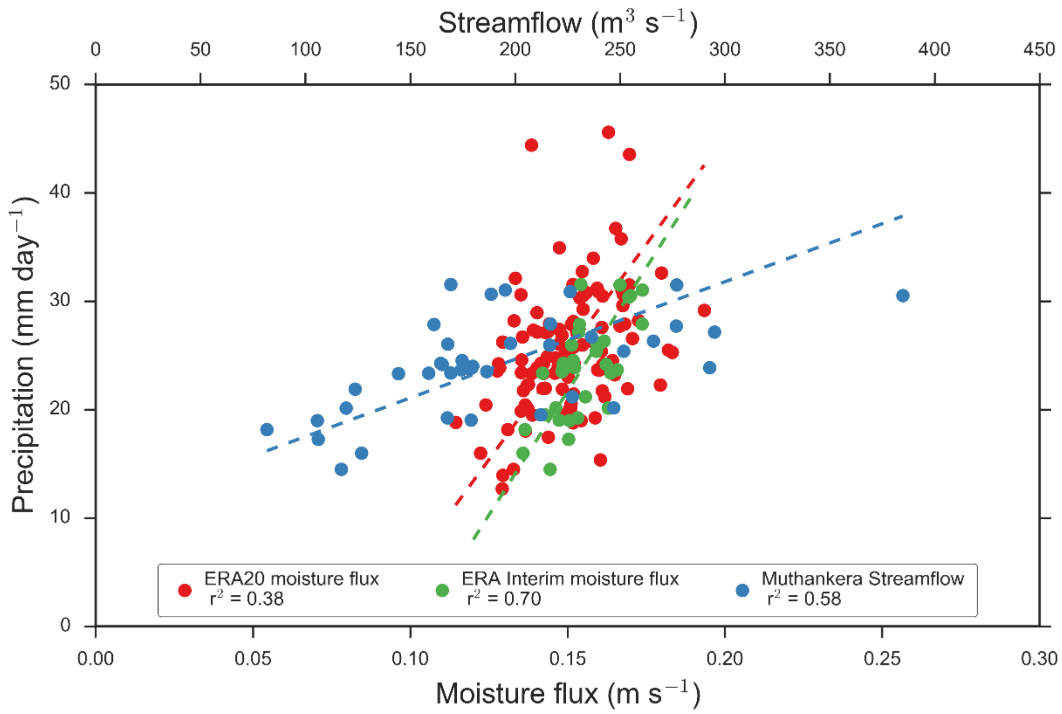


Figure 4: Relationship between re-analysis moisture flux and observed precipitation; and observed streamflow and observed precipitation.

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 1b).

5. Discussion and conclusions

We have developed a new method to characterise 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 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 few studies that applied expert judgment in a regional climate change context did so with climate model output. Mearns et al. (2017) used expert elicitation to determine the differential credibility of regional climate change simulations while Risbey et al. (2002) used expert judgment techniques to explore the structure of regional climate scenarios. Our approach is not constrained by climate model output; therefore, it is more comprehensive because the elicitation process requires experts to consider multiple lines of evidence that include theory, observations and model results. This led to the exploration of uncertainty spaces for which no current literature exists – for example the cooling of sea surface temperatures which would reduce available moisture – which was deemed plausible but of low likelihood by the experts. 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).

Our approach is one of several expert judgments 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. 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 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 demonstrated the usefulness of qualitative narratives and associated quantitative time series of precipitation change to examine long-term water resources planning in the CRBK. Expert judgment techniques should be more widely applied to characterise uncertainty in regional and local climate change.

References

BAMBER, J. L. & ASPINALL, W. P. 2013. An expert judgement assessment of future sea level rise from the ice sheets. *Nature Clim. Change,* 3**,** 424-427.

BECKER, A., FINGER, P., MEYER-CHRISTOFFER, A., RUDOLF, B., SCHAMM, K., SCHNEIDER, U. & ZIESE, M. 2013. A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present. *Earth Syst. Sci. Data,* 5**,** 71-99.

BHAVE, A. G., CONWAY, D., DESSAI, S. & STAINFORTH, D. A. 2018. Water resource planning under future climate and socio-economic uncertainty in the Cauvery River Basin in Karnataka, India. *Water Resources Research***,** (accepted).

BOLLASINA, M. A., MING, Y. & RAMASWAMY, V. 2011. Anthropogenic Aerosols and the Weakening of the South Asian Summer Monsoon. *Science,* 334**,** 502-505.

CHERCHI, A. & NAVARRA, A. 2013. Influence of ENSO and of the Indian Ocean Dipole on the Indian summer monsoon variability. *Climate Dynamics,* 41**,** 81-103.

DEE, D. P., UPPALA, S. M., SIMMONS, A. J., BERRISFORD, P., POLI, P., KOBAYASHI, S., ANDRAE, U., BALMASEDA, M. A., BALSAMO, G., BAUER, P., BECHTOLD, P., BELJAARS, A. C. M., VAN DE BERG, L., BIDLOT, J., BORMANN, N., DELSOL, C., DRAGANI, R., FUENTES, M., GEER, A. J., HAIMBERGER, L., HEALY, S. B., HERSBACH, H., HÓLM, E. V., ISAKSEN, L., KÅLLBERG, P., KÖHLER, M., MATRICARDI, M., MCNALLY, A. P., MONGE-SANZ, B. M., MORCRETTE, J. J., PARK, B. K., PEUBEY, C., DE ROSNAY, P., TAVOLATO, C., THÉPAUT, J. N. & VITART, F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society,* 137**,** 553-597.

FIELD, C. B., BARROS, V. R., MACH, K. J., MASTRANDREA, M. D., AALST, M. V., ADGER, W. N., ARENT, D. J., BARNETT, J., BETTS, R., BILIR, T. E., BIRKMANN, J., CARMIN, J., CHADEE, D. D., CHALLINOR, A. J., CHATTERJEE, M., CRAMER, W., DAVIDSON, D. J., ESTRADA, Y. O., GATTUSO, J. P., HIJIOKA, Y., HOEGH-GULDBERG, O., HUANG, H. Q., INSAROV, G. E., JONES, R. N., KOVATS, R. S., LANKAO, P. R., LARSEN, J. N., LOSADA, I. J., MARENGO, J. A., MCLEAN, R. F., MEARNS, L. O., MECHLER, R., MORTON, J. F., NIANG, I., OKI, T., OLWOCH, J. M., OPONDO, M., POLOCZANSKA, E. S., PÖRTNER, H. O., REDSTEER, M. H., REISINGER, A., REVI, A., SCHMIDT, D. N., SHAW, M. R., SOLECKI, W., STONE, D. A., STONE, J. M. R., STRZEPEK, K. M., SUAREZ, A. G., TSCHAKERT, P., VALENTINI, R., VICUÑA, S., VILLAMIZAR, A., VINCENT, K. E., WARREN, R., WHITE, L. L., WILBANKS, T. J., WONG, P. P. & YOHE, G. W. 2014. Technical Summary. *In:* FIELD, C. B., BARROS, V. R., DOKKEN, D. J., MACH, K. J., MASTRANDREA, M. D., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A.

N., MACCRACKEN, S., MASTRANDREA, P. R. & WHITE, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

GOSLING, J. P. 2018. SHELF: the Sheffield elicitation framework. *In:* DIAS, L. C., MORTON, A. & QUIGLEY, J. (eds.) *The Science and Art of Structuring Judgement.* Springer.

GUNNELL, Y. 1997. Relief and climate in South Asia: the influence of the western ghats on the current climate pattern of peninsular India. *International Journal of Climatology,* 17**,** 1169-1182.

HAZELEGER, W., VAN DEN HURK, B. J. J. M., MIN, E., VAN OLDENBORGH, G. J., PETERSEN, A. C., STAINFORTH, D. A., VASILEIADOU, E. & SMITH, L. A. 2015. Tales of future weather. *Nature Clim. Change,* 5**,** 107-113.

HEWITSON, B., JANETOS, A. C., CARTER, T. R., GIORGI, F., JONES, R. G., KWON, W. T., MEARNS, L. O., SCHIPPER, E. L. F. & AALST, M. V. 2014. Regional context. *In:* BARROS, V. R., FIELD, C. B., DOKKEN, D. J., MASTRANDREA, M. D., MACH, K. J., BILIR, T. E., CHATTERJEE, M., EBI, K. L., ESTRADA, Y. O., GENOVA, R. C., GIRMA, B., KISSEL, E. S., LEVY, A. N., MACCRACKEN, S., MASTRANDREA, P. R. & WHITE, L. L. (eds.) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

JAMES, R., WASHINGTON, R. & JONES, R. 2015. Process-based assessment of an ensemble of climate projections for West Africa. *Journal of Geophysical Research: Atmospheres,* 120**,** 1221-1238.

JOSEPH, P. V. & SIJIKUMAR, S. 2004. Intraseasonal Variability of the Low-Level Jet Stream of the Asian Summer Monsoon. *Journal of Climate,* 17**,** 1449-1458.

KANDLIKAR, M., RISBEY, J. & DESSAI, S. 2005. Representing and communicating deep uncertainty in climate-change assessments. *Comptes Rendus Geoscience,* 337**,** 443-455.

KNUTTI, R. & SEDLACEK, J. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Clim. Change,* 3**,** 369-373.

KRIEGLER, E., HALL, J. W., HELD, H., DAWSON, R. & SCHELLNHUBER, H. J. 2009. Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences,* 106**,** 5041-5046.

KRISHNAN, R., SABIN, T. P., VELLORE, R., MUJUMDAR, M., SANJAY, J., GOSWAMI, B. N., HOURDIN, F., DUFRESNE, J.-L. & TERRAY, P. 2016. Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. *Climate Dynamics,* 47**,** 1007-1027.

LEVINE, R. C. & TURNER, A. G. 2012. Dependence of Indian monsoon rainfall on moisture fluxes across the Arabian Sea and the impact of coupled model sea surface temperature biases. *Climate Dynamics,* 38**,** 2167-2190.

MEARNS, L. O., BUKOVSKY, M. S. & SCHWEIZER, V. J. 2017. Potential Value of Expert Elicitation for Determining Differential Credibility of Regional Climate Change Simulations: An Exercise with the NARCCAP co-PIs for the Southwest Monsoon Region of North America. *Bulletin of the American Meteorological Society,* 98**,** 29-35.

MORGAN, M. G. & KEITH, D. W. 1995. Climate-Change - Subjective Judgments by Climate Experts. *Environmental Science & Technology,* 29**,** A468-A476.

NIYOGI, D., KISHTAWAL, C., TRIPATHI, S. & GOVINDARAJU, R. S. 2010. Observational evidence that agricultural intensification and land use change may be reducing the Indian summer monsoon rainfall. *Water Resources Research,* 46**,** W03533.

O'HAGAN, A., BUCK, C. E., DANESHKHAH, A., EISER, J. R., GARTHWAITE, P. H., JENKINSON, D. J., OAKLEY, J. E. & RAKOW, T. 2006. *Uncertain judgements: eliciting experts' probabilities*, John Wiley & Sons.

OAKLEY, J. E. & O'HAGAN, A. 2016. *SHELF: the Sheffield elicitation framework (version 3.0)* [Online]. Available: http://www.tonyohagan.co.uk/shelf/ [Accessed].

PARKER, W. S. & RISBEY, J. S. 2015. False precision, surprise and improved uncertainty assessment. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences,* 373**,** 20140453.

POLI, P., HERSBACH, H., DEE, D. P., BERRISFORD, P., SIMMONS, A. J., VITART, F., LALOYAUX, P., TAN, D. G. H., PEUBEY, C., THÉPAUT, J.-N., TRÉMOLET, Y., HÓLM, E. V., BONAVITA, M., ISAKSEN, L. & FISHER, M. 2016. ERA-20C: An Atmospheric Reanalysis of the Twentieth Century. *Journal of Climate,* 29**,** 4083-4097.

RISBEY, J. S., LAMB, P. J., MILLER, R. L., MORGAN, M. C. & ROE, G. H. 2002. Exploring the Structure of Regional Climate Scenarios by Combining Synoptic and Dynamic Guidance and GCM Output. *Journal of Climate,* 15**,** 1036-1050.

ROY, I., TEDESCHI, R. G. & COLLINS, M. 2017. ENSO teleconnections to the Indian summer monsoon in observations and models. *International Journal of Climatology,* 37**,** 1794-1813.

RUANE, A. C., TEICHMANN, C., ARNELL, N. W., CARTER, T. R., EBI, K. L., FRIELER, K., GOODESS, C. M., HEWITSON, B., HORTON, R., KOVATS, R. S., LOTZE, H. K., MEARNS, L. O., NAVARRA, A., OJIMA, D. S., RIAHI, K., ROSENZWEIG, C., THEMESSL, M. & VINCENT, K. 2016. The Vulnerability, Impacts, Adaptation and Climate Services Advisory Board (VIACS AB v1.0) contribution to CMIP6. *Geosci. Model Dev.,* 9**,** 3493-3515.

SAEED, F., HAGEMANN, S. & JACOB, D. 2009. Impact of irrigation on the South Asian summer monsoon. *Geophysical Research Letters,* 36**,** n/a-n/a.

SAJANI, S., SULOCHANA, G., FRANCIS, P. A. & RAJEEVAN, M. 2015. Prediction of Indian rainfall during the summer monsoon season on the basis of links with equatorial Pacific and Indian Ocean climate indices. *Environmental Research Letters,* 10**,** 094004.

SANDEEP, S. & AJAYAMOHAN, R. S. 2015. Poleward shift in Indian summer monsoon low level jetstream under global warming. *Climate Dynamics,* 45**,** 337-351.

SHEPHERD, T. G. 2014. Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geosci,* 7**,** 703-708.

STEVENS, B., SHERWOOD, S. C., BONY, S. & WEBB, M. J. 2016. Prospects for narrowing bounds on Earth's equilibrium climate sensitivity. *Earth's Future,* 4**,** 512-522.

THOMPSON, E., FRIGG, R. & HELGESON, C. 2016. Expert Judgment for Climate Change Adaptation. *Philosophy of Science,* 83**,** 1110-1121.

VAN 'T KLOOSTER, S. A. & VAN ASSELT, M. B. A. 2006. Practising the scenario-axes technique. *Futures,* 38**,** 15-30.

VANHAM, D., WEINGARTNER, R. & RAUCH, W. 2011. The Cauvery river basin in Southern India: major challenges and possible solutions in the 21st century. *Water Science and Technology,* 64**,** 122-131.

WANG, Z., LI, G. & YANG, S. 2017. Origin of Indian summer monsoon rainfall biases in CMIP5 multimodel ensemble. *Climate Dynamics***,** (in press).

ZAPPA, G. & SHEPHERD, T. G. 2017. Storylines of Atmospheric Circulation Change for European Regional Climate Impact Assessment. *Journal of Climate,* 30**,** 6561-6577.

Supplementary Information

Supplementary information 1: Expert elicitation workshop

We conducted an expert elicitation workshop in London on the 10th July 2015 for half a day (four hour) with eight experts in the ISM (Table 1 lists the experts' area of expertise and country). The experts were recruited opportunistically from their attendance of a workshop on "Linkages between air pollution and climate change in South Asia" the previous day (https://www.imperial.ac.uk/grantham/news-and-events/events/lorri-workshop/).

Expert's country	Expertise
UK	Monsoon variability, predictability and prediction and the interaction between monsoon systems and other elements of the climate system
India	Variability and trends of Indian Summer Monsoon systems, monsoon-aerosol interactions and climate/meso-scale models
India	Short to seasonal time scale monsoon prediction, Indian Summer Monsoon processes, convection systems, aerosols and surface hydrology
India	Natural aerosols, aerosol cloud climate interactions and influence on the Indian Summer Monsoon
UK	Mechanisms and physical processes controlling past and future changes in regional hydroclimate at seasonal to interdecadal time scales, focussing on local and long distance aerosols and impact on Indian Summer Monsoon
India	Climate modelling and impacts of climate change
UK	Solar influence on climate variability related to the Indian Summer Monsoon and ENSO as a teleconnection for the Indian Summer Monsoon
UK	Tropical convection and clouds in weather and climate models, monsoon systems and impact of land-surface changes on clouds and rainfall

Table 1. Expert's area of expertise and country of work.

Supplementary information 2: List of identified key processes influencing Indian Summer Monsoon precipitation

1. Anthropogenic aerosols
2. ENSO (seasonal)
3. Land-sea temp contrast (long term) / tropospheric temperature gradient
4. Atmospheric stability in the region
5. Natural Aerosols
6. Land use / cover change
7. Variation of ITCZ
8. Decadal variability in the ocean (Pacific Decadal Oscillation, Atlantic Decadal Oscillation)
9. Increase in temp and its effects on how much moisture the atmosphere can hold (water holding capacity)
10. South-East and North-East monsoon
11. Remote impacts of pollution (e.g. in China)
12. Changes in the albedo of snow due to deposition of Black Carbon aerosols in Northern India (snow and aerosol is important as large-scale driver)
13. Indian ocean variability (Indian Ocean Dipole, Equatorial Indian Ocean Oscillation) – akin to ENSO – driver on inter-annual timescales
14. Sea Surface Temperature (SST) in Bay of Bengal and Arabian Sea
15. Local use of ground and surface water. Land use practice in relation to how much water is kept in basin, how it is used and implications for moisture recycling in the basin
16. Large scale changes in the tropical circulation (changes in Hadley and Walker cells) – supposed to spin down (weaken) with global warming
17. Mid-latitude Hadley Circulation
18. Axis of Somali Jet (moisture transport is a cause as well as consequence, so it is a feedback)
19. Intra Seasonal Variability or Active break cycles
20. Albedo of Tibetan plateau (melting due to warming, exacerbated by aerosol)
21. Indirect effects of aerosols
22. Madden Julian Oscillation (MJO)
23. Cyclones and monsoon depressions

Supplementary information 3: Climate processes influence in the Indian Summer Monsoon and moisture flow

Brief explanations of how the ten key processes elicited by experts can influence the ISM and moisture flow according to peer-reviewed literature.

1. Arabian Sea/Indian Ocean Sea Surface Temperature (SST) – The Arabian Sea/Indian Ocean play an important role in supplying moisture to the ISM, and hence strongly influences ISM rainfall. The Indian Ocean SSTs influence the ISM through their impact on the seasonal heat and moisture transport and monsoon winds (Turner and Annamalai, 2012). Roxy et al. (2015) and Weller et al. (2016) have discussed in detail paleoclimate studies, modelling studies and recent observations related to SSTs and how variations have or could influence ISM precipitation.
2. Global Warming – Experts used this term to describe the recent and expected future global mean temperature increase. The ISM is highly sensitive to global warming, as indicated by the projected changes in extreme precipitation (Kitoh et al. 2013; Sharmila et al. 2015). Turner and Annamalai (2012) have reviewed ISM modelling studies, and discuss that global temperature increase results in an increase in ISM rainfall primarily through two mechanisms; increased land-sea temperature contrast, and greater atmospheric moisture content over a warmer Indian Ocean.
3. Horizontal tropospheric Temperature Gradient – The atmospheric temperature contrast between the land and ocean is a key driver of the ISM, and so ISM rainfall will be sensitive to/affected by any changes to this thermal gradient (Chou 2003; Kumar et al. 2013; Roxy et al. 2015).
4. Himalayan Snow Cover – The extent of snow cover across Eurasia and particularly in the Himalayas has an inverse relationship with ISM rainfall (Vernekar et al. 1995), and several studies have investigated the underlying mechanisms (Halder and Dimeyer, 2016). Winter snowfall in the Himalayas is primarily driven by western disturbances, and this snow cover affects regional albedo characteristics, decreasing atmospheric temperatures and thus weakening the land-sea temperature contrast, which further affects the onset and rainfall of the succeeding ISM (Dimri et al. 2015).
5. Anthropogenic Aerosol Forcing – Aerosols of anthropogenic origin affect the atmospheric absorption of solar radiation, increase the brightness of clouds and decrease their precipitation efficiency, all of which suppresses precipitation (Ramanathan et al. 2001). Enhanced anthropogenic aerosols in the 20^{th} century have affected the onset of ISM (Bollasina et al. 2013) and can explain the decreasing trend of observed ISM precipitation (Bollasina et al. 2011; Krishnan et al. 2015).
6. Inter Tropical Convergence Zone (ITCZ) Movement Northwards – The ITCZ is an area encircling the globe where the northeast and southeast trade winds converge, producing a band of clouds across the tropics. Its seasonal movement northward has been linked to the onset of the ISM (Saha and Saha, 1980; Gadgil 2003). The mean position of the

ITCZ moves from ~5 °S in winter to ~20 °N during the northern summer (Goswami 2005), and fluctuations in its location affects wet and dry spells, and precipitation extremes (Singh et al. 2014).

7. Strength of Westerly Jet – A strong cross-equatorial low level jet stream is seen across the Indian Ocean and India from June-September. This jet, also called the Westerly Jet or Somali Jet, transports moisture from the Indian Ocean to the South Asian land mass at an altitude of ~1.5 km above mean sea level (Joseph and Sijikumar 2004), and it weakens during monsoon withdrawal (Sabeerali et al. 2012). Observations and future CMIP5 projections indicate a poleward shift of the Westerly Jet, which is changing the spatial distribution and amount of ISM precipitation (Sandeep and Ajayamohan 2015).
8. Extent of Irrigation – Irrigation water use alters the hydrological cycle by reducing river base flow and increasing evapotranspiration, which can influence cloud development. Across India's heavily irrigated regions, vapour and energy fluxes are changing due to changes in land use, affecting precipitation patterns and large scale monsoon circulation (Douglas et al. 2006). Observations and model-based simulations also indicate that the extent and timing of irrigation strongly reduces ISM precipitation by weakening the tropospheric temperature gradient (Saeed et al. 2009; Niyogi et al. 2010; Shukla et al. 2014).
9. Influence of dry northerlies – There is growing recognition that dry warm winds coming over the Persian plateau and Pakistan reduces the moisture content of the Westerly Jet (Annamalai and Sperber 2005; Prasanna and Annamalai 2011; Muraleedharan et al. 2013), and the moistening of this dry layer may play a key role in the onset of the ISM (Parker et al. 2016), although experts suggested that this is work in progress.
10. Influential teleconnections – El Niño/La Niña: The influence of the El Niño Southern Oscillation on the ISM, as a teleconnection is well researched (Cherchi and Navarra 2013, Roy et al. 2017). El Niño occurrence is strongly associated with reduced ISM precipitation, and is considered an important factor affecting its inter-annual variability. Modelling results indicate that this relationship will sustain in a warming world (Turner and Annamalai 2012). The Equatorial Indian Ocean Oscillation (EQUINOO) plays an important role in influencing the inter-annual variability of ISM precipitation, and explains 19% of the variance (Gadgil et al. 2007). It is considered to be the atmospheric component of the Indian Ocean Dipole, and its positive phase is associated with greater precipitation, while the negative phase is associated with reduced ISM precipitation (Surendran et al. 2015).

References

Annamalai, H., & Sperber, K. R. (2005). Regional heat sources and the active and break phases of boreal summer intraseasonal (30–50 day) variability. Journal of the atmospheric sciences, 62(8), 2726-2748.

Bollasina, M. A., Ming, Y., & Ramaswamy, V. (2011). Anthropogenic aerosols and the weakening of the South Asian summer monsoon. Science, 334(6055), 502-505.

Bollasina, M. A., Ming, Y., & Ramaswamy, V. (2013). Earlier onset of the Indian monsoon in the late twentieth century: The role of anthropogenic aerosols. Geophysical Research Letters, 40(14), 3715-3720.

Cherchi, A., & Navarra, A. (2013). Influence of ENSO and of the Indian Ocean Dipole on the Indian summer monsoon variability. Climate dynamics, 41(1), 81.

Chou, C. (2003). Land–sea heating contrast in an idealized Asian summer monsoon. Climate Dynamics, 21(1), 11-25.

Dimri, A. P., Niyogi, D., Barros, A. P., Ridley, J., Mohanty, U. C., Yasunari, T., & Sikka, D. R. (2015). Western disturbances: a review. Reviews of Geophysics, 53(2), 225-246.

Gadgil, S. (2003). The Indian monsoon and its variability. Annual Review of Earth and Planetary Sciences, 31(1), 429-467.

Gadgil, S., Rajeevan, M., & Francis, P. A. (2007). Monsoon variability: Links to major oscillations over the equatorial Pacific and Indian oceans. Current Science, 93(2), 182-194.

Goswami, B. N. (2005). South Asian monsoon. In Intraseasonal variability in the atmosphere-ocean climate system, Lau, W. K., Waliser, D. E. (eds) (pp. 21-72). Springer Berlin Heidelberg.

Halder, S., & Dirmeyer, P. A. (2017). Relation of Eurasian Snow Cover and Indian Summer Monsoon Rainfall: Importance of the Delayed Hydrological Effect. Journal of Climate, 30(4), 1273-1289.

Joseph, P. V., & Sijikumar, S. (2004). Intraseasonal variability of the low-level jet stream of the Asian summer monsoon. Journal of Climate, 17(7), 1449-1458.

Kitoh, A., Endo, H., Krishna Kumar, K., Cavalcanti, I. F., Goswami, P., & Zhou, T. (2013). Monsoons in a changing world: a regional perspective in a global context. Journal of Geophysical Research: Atmospheres, 118(8), 3053-3065.

Krishnan, R., Sabin, T. P., Vellore, R., Mujumdar, M., Sanjay, J., Goswami, B. N., Hourdin, F., Dufresne, J. L. & Terray, P. (2015). Deciphering the desiccation trend of the South Asian monsoon hydroclimate in a warming world. Climate dynamics, 47(3), 1007-1027.

Kumar, K. N., Rajeevan, M., Pai, D. S., Srivastava, A. K., & Preethi, B. (2013). On the observed variability of monsoon droughts over India. Weather and Climate Extremes, 1, 42-50.

Muraleedharan, P. M., Mohankumar, K., & Sivakumar, K. U. (2013). A study on the characteristics of temperature inversions in active and break phases of Indian summer monsoon. Journal of Atmospheric and Solar-Terrestrial Physics, 93, 11-20.

Niyogi, D., Kishtawal, C., Tripathi, S., & Govindaraju, R. S. (2010). Observational evidence that agricultural intensification and land use change may be reducing the Indian summer monsoon rainfall. Water Resources Research, 46(3).

Parker, D. J., P. Willetts, C. Birch, A. G. Turner, J. H. Marsham, C. M. Taylor, S. Kolusu & G. M. Martin (2016). The interaction of moist convection and mid-level dry air in the advance of the onset of the Indian monsoon. Quarterly Journal of the Royal Meteorological Society, 142(699): 2256-2272.

Prasanna, V., & Annamalai, H. (2012). Moist dynamics of extended monsoon breaks over South Asia. Journal of Climate, 25(11), 3810-3831.

Ramanathan, V. C. P. J., Crutzen, P. J., Kiehl, J. T., & Rosenfeld, D. (2001). Aerosols, climate, and the hydrological cycle. science, 294(5549), 2119-2124.

Roxy, M. K., Ritika, K., Terray, P., Murtugudde, R., Ashok, K., & Goswami, B. N. (2015). Drying of Indian subcontinent by rapid Indian Ocean warming and a weakening land-sea thermal gradient. Nature communications, 6, 7423.

Roy, I., R. G. Tedeschi & M. Collins (2017). ENSO teleconnections to the Indian summer monsoon in observations and models. International Journal of Climatology, 37(4): 1794-1813.

Sabeerali, C. T., Rao, S. A., Ajayamohan, R. S., & Murtugudde, R. (2012). On the relationship between Indian summer monsoon withdrawal and Indo-Pacific SST anomalies before and after 1976/1977 climate shift. Climate dynamics, 39(3), 841-859.

Saeed, F., Hagemann, S., & Jacob, D. (2009). Impact of irrigation on the South Asian summer monsoon. Geophysical Research Letters, 36(20).

Saha, S., & Saha, K. (1980). A hypothesis on onset, advance and withdrawal of the Indian summer monsoon. Pure and applied geophysics, 118(2), 1066-1075.

Sandeep, S., & Ajayamohan, R. S. (2015). Poleward shift in Indian summer monsoon low level jetstream under global warming. Climate Dynamics, 45(1-2), 337.

Sharmila, S., Joseph, S., Sahai, A. K., Abhilash, S., & Chattopadhyay, R. (2015). Future projection of Indian summer monsoon variability under climate change scenario: An assessment from CMIP5 climate models. Global and Planetary Change, 124, 62-78.

Shukla, S. P., Puma, M. J., & Cook, B. I. (2014). The response of the South Asian Summer Monsoon circulation to intensified irrigation in global climate model simulations. Climate Dynamics, 42(1-2), 21-36.

Singh, D. (2016). South Asian monsoon: Tug of war on rainfall changes. Nature Clim. Change, 6(1): 20-22.

Singh, D., Tsiang, M., Rajaratnam, B., & Diffenbaugh, N. S. (2014). Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. Nature Climate Change, 4(6), 456-461.

Surendran, S., Gadgil, S., Francis, P. A., & Rajeevan, M. (2015). Prediction of Indian rainfall during the summer monsoon season on the basis of links with equatorial Pacific and Indian Ocean climate indices. Environmental Research Letters, 10(9), 094004.

Turner, A. G., & Annamalai, H. (2012). Climate change and the South Asian summer monsoon. Nature Climate Change, 2(8), 587-595.

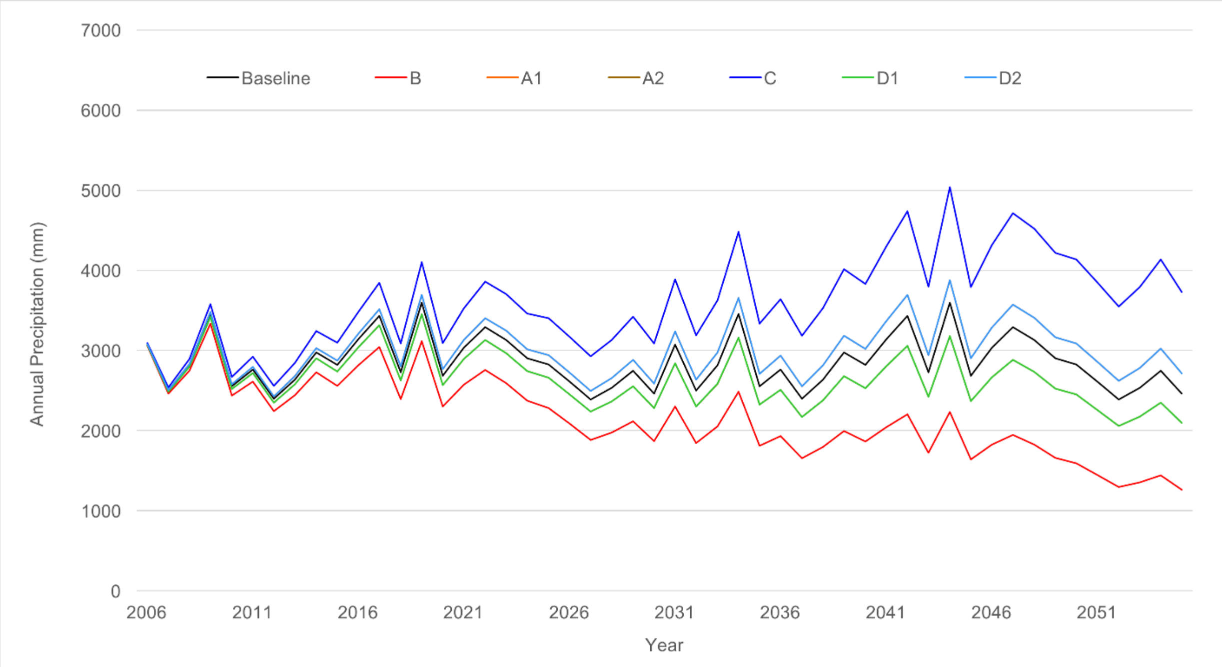
Vernekar, A. D., Zhou, J., & Shukla, J. (1995). The effect of Eurasian snow cover on the Indian monsoon. Journal of Climate, 8(2), 248-266.

Weller, E., Min, S. K., Cai, W., Zwiers, F. W., Kim, Y. H., & Lee, D. (2016). Human-caused Indo-Pacific warm pool expansion. Science advances, 2(7), e1501719.

Supplementary information 4: Examples of translating qualitative narratives into illustrative quantitative time series of precipitation change

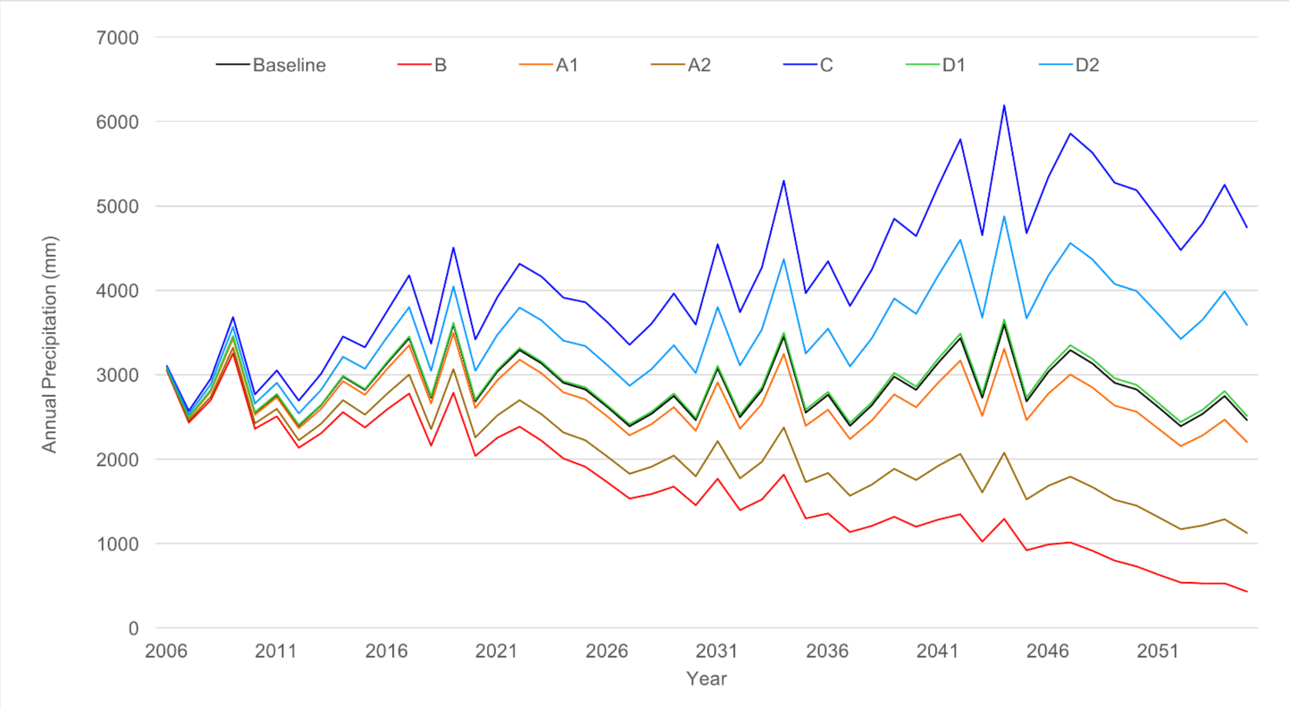
Many climate impact models – e.g., a water resources model – require quantitative time series of future climate to estimate the impact of climate change. Here we show how qualitative climate narratives can be translated into illustrative quantitative time series of precipitation change which could be used in such studies; one of these examples has been used in a related study of adaptation options in water resources planning in the CRBK (Bhave et al. 2018). The least squares regression line equation for ERA Interim is: y = 434.8x - 43.95, where x is the independent variable moisture flux (m s-1), and y is the dependent variable precipitation (mm day-1).

In the first illustrative example, akin to a sensitivity test, we followed the 1:1 line to determine the change factors for the drivers. For narratives A, B, C and D we applied a ±10% change factor in both variables (moisture availability and strength of flow), while for narratives A1, A2, D1 and D2 we applied a ±5% change factor for the variable with less influence and ±10% for the variable with greater influence. The modified moisture fluxes for each narrative were used to calculate average future precipitation using the regression relationship above. The narratives provided no information on changes in precipitation variability - the experts thought changes in interannual variability were too uncertain to estimate. Monthly observed precipitation data were available for the 25-year period from 1981-2005 through the Global Precipitation Climatology Centre. We derived illustrative 50-year time series from 2006 to 2055 for each narrative by assuming a linear rate of change from the average baseline precipitation (1981-2005) to narrative specific average future precipitation and applying it to the 25-year observed precipitation twice. Incremental changes at a monthly time step were applied to the baseline precipitation time series to develop a quantitative precipitation time series consistent with the qualitative narrative description (SI Figure 1).



SI Figure 1. Illustrative example of future average annual precipitation of Western Ghats regions for six climate narratives (following the 1:1 line for determining the change factors for the drivers) and baseline precipitation. Note that A1 and D2 overlap as does A2 and D1.

The second illustrative example uses the results of the climate analysis (Section 4) to determine the change factors for the drivers. We used the 2 standard deviation box for the ERA Interim results (in Figure 3) to estimate the change factors. For narratives A, B, C and D we applied a ±10% change factor for moisture availability and ±25% for strength of flow. For example, for Narrative C we applied +10% for moisture availability and +25% for strength of flow. For narratives A1, A2, D1 and D2 we applied a ±5% change factor for moisture availability and ±12.5% for strength of flow depending on which variable has greater influence. For example, for Narrative A1 we applied +10% for moisture availability and -12.5% for strength of flow. The time series were then calculated the same way as the previous example (SI Figure 2)

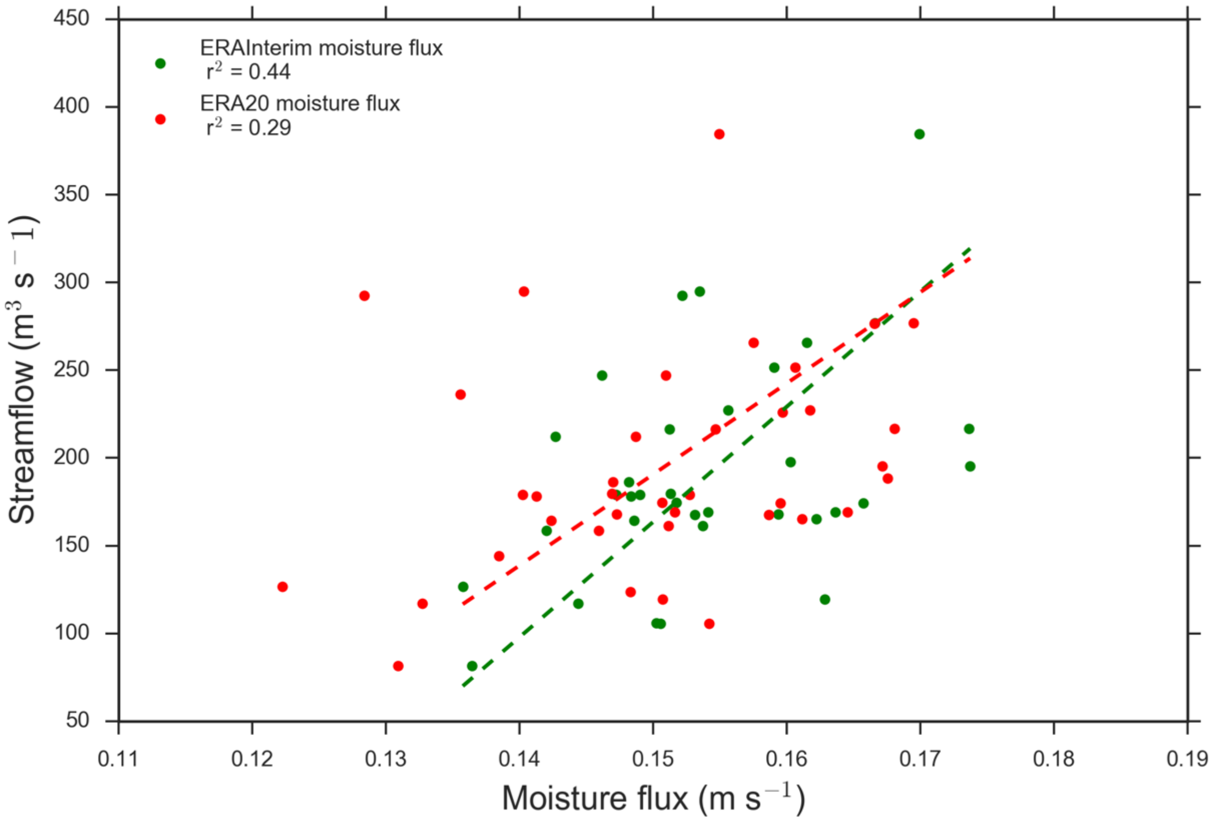


SI Figure 2. Illustrative example of future average annual precipitation of Western Ghats regions for six climate narratives (following the 2 standard deviation box for the ERA Interim results for determining the change factors for the drivers) and baseline precipitation.

References

Bhave, A.G., D. Conway, S. Dessai and D.A. Stainforth (2018) Water resource planning under future climate and socio-economic uncertainty in the Cauvery River Basin in Karnataka, India. *Water Resources Research* (in press).

Supplementary information 5: Relationship between moisture flux and observed streamflow at Muthankera



SI Figure 3. 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 (1973-2010), ERA Interim (1979-2012) - and observed streamflow at Muthankera (green diamond in Figure 1b).

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

Narrative A describes future evolution of the Indian Summer Monsoon (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 a scenario of 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 warming 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 of 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 warming and reduction in Himalayan snow cover, leading to an intensification of the tropospheric temperature gradient.