

Interaction of Convective Organization and Monsoon Precipitation, Atmosphere, Surface and Sea (INCOMPASS) – Case for Support Part 2: The Science Case

Summary

This project will advance our ability to forecast the monsoon, through a programme of measurements and modelling that aims to capture the key surface-atmosphere feedback processes in models. The monsoon supplies the majority of water in South Asia, and the growing population and economy therefore make understanding and predicting the system vital. Modelling and forecasting the monsoon from days to the season ahead is limited by large model errors that develop quickly, with significant model-to-model differences pointing to errors in physical parametrizations such as convection, boundary layer and land surface. These errors persist into climate projections and some are not diminished by increasing resolution. At the same time, a lack of detailed observations is preventing a more thorough understanding of monsoon circulation and its interaction with the land surface; a process governed by boundary layer and convective cloud dynamics. This project will **support and develop modelling capability** in Indo-UK monsoon research, including test development of a new 100m-resolution domain over India. The first UK detachment of the FAAM research aircraft to India, in combination with an intensive ground-based observation campaign, will gather **new observations of the surface, boundary layer structure and atmospheric profiles** to go with detailed information on the timing of monsoon rainfall. Observations will be focused on three transects: in the northern plains of India, covering a range of surface types from irrigated to rain-fed agriculture, and wet to dry climatic zones; and across the Western Ghats, and rain shadow, including transitions from land to ocean and across orography. The observational analysis will allow a **unique and unprecedented characterisation of monsoon processes** that will feed directly into model development at the Met Office and NCMRWF, through model evaluation at a range of scales and model improvement by working with parametrization developers. The project will institute a **new long-term series of measurements of land surface fluxes**, a particularly unconstrained observation for India, through eddy covariance flux towers. Combined with detailed land surface modelling using JULES, this will allow testing of land surface initialisation in monsoon forecasts and improved land-atmosphere coupling. This project will cooperate with two sister proposals, measuring ocean-atmosphere coupling and aerosol-monsoon processes, if funded. The combination of new detailed observations and model development in this work will improve our models and produce better predictions of the monsoon.

Science background

The South Asian monsoon affects the lives of more than a billion people, supplying up to 80% of annual rainfall during the summer months (June-September). Relatively small interannual variability (the standard deviation is only around 10% of the seasonal-mean rainfall) finely ties society to the timing, intensity and duration of the monsoon, its variations causing problems in agriculture and industry, loss of GDP in drought (Gadgil & Gadgil, 2006) and tremendous flood damage (e.g., in Pakistan, 2010; Lau & Kim, 2011, and in northern India during 2013). Despite the importance of the monsoon to human well-being, seasonal forecasting of the monsoon remains a problem (Rajeevan, et al., 2012), with ensemble prediction skill for summer monsoon rainfall reaching correlation scores of only 0.4 over small parts of India. The latest generation of Coupled Model Intercomparison Project climate models has made improvements in all aspects of monsoon simulation and variability since the previous generation but there are still major dry biases over India (Sperber et al., 2013) not limited to the Met Office Unified Model (MetUM). Large-scale monsoon rainfall biases are common from NWP to climate scales, often developing in the first few days allowing seamless approaches to understand them (e.g., examining evolution of NWP error to understand those in climate models: Martin et al., 2010; Mitra et al., 2013).

The rainfall pattern in India through the season (Fig. 1) reveals considerable spatial heterogeneity. Orographic effects on the mean flow enhance rainfall in the wet regions of the Western Ghats, while in the northeast peninsula synoptic low-pressure systems or monsoon depressions are prevalent. These systems track north-westwards, from the warm moist inflow region of the northern Bay of Bengal, across the peninsula and yield much of the rainfall (Krishnamurthy & Shukla, 2007). Figure 1 also reveals the evolution of the monsoon through the season. Onset occurs first over the southwest coast, before spreading up the west coast as the monsoon flow moves northwards. Simultaneously, continuation of the westerly flow across the Bay of Bengal eventually turns

cyclonically around the monsoon trough, bringing rain to Bangladesh and the northeast states. As the monsoon matures it expands northwest towards Pakistan, covering India by around mid-July. At the season-end the monsoon withdraws in the opposite direction. In consequence, the northwest is much drier (the Thar Desert in Rajasthan) and has less frequent rainfall. The contrast between the wet Bay of Bengal and dry northwest is supported by feedbacks on Rossby wave-forced descent (e.g. Bollasina & Nigam, 2011). This evolution and spatial contrast informs the design of our field campaign (see later).

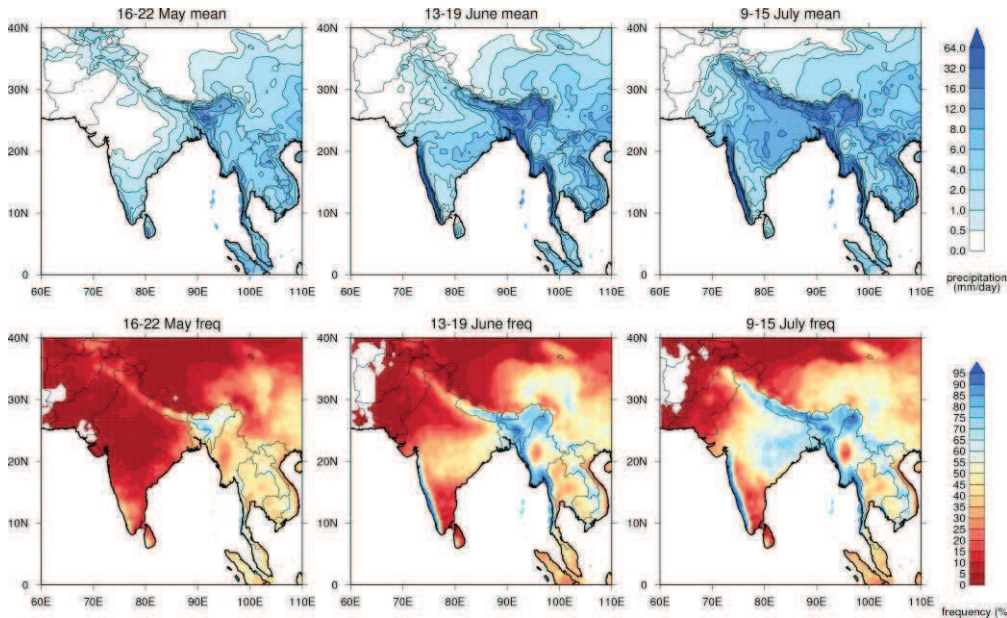


Figure 1. Top: mean rainfall during weeks in mid-May, mid-June and mid-July from daily APRHODITE 0.5° gridded data of monsoon Asia, averaged 1951-2007. Bottom: daily frequency of rainfall in the same periods, using a rainfall threshold of 2.5 mm/day.

Figure 2 below demonstrates the orographic distribution and use of irrigation for agriculture. The Indo-Gangetic Plains (IGP) in the north feature extensive irrigation and represent the breadbasket of India. The irrigated surface energy balance contrasts strongly with semi-arid conditions elsewhere in

northern India and coincides with the monsoon trough (Fig. 2). Northern India has been shown as a ‘hotspot’ of coupling between soil moisture and precipitation in models (Koster et al., 2004). Modelling work has shown the IGP to have a strong bearing on the development of the monsoon in models and in the diurnal cycle of boundary layer structure (Turner et al., 2013), however **high frequency observations are lacking for comparison.**

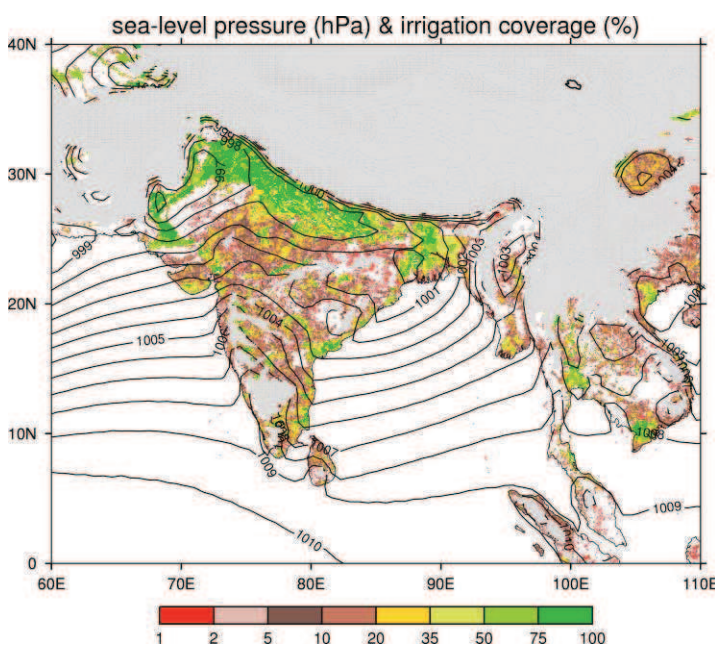


Figure 2. Mean SLP from ERA-Interim showing the monsoon trough, averaged JJA 1979-2012 (contours) & fraction of land equipped for irrigation (coloured shading) from FAO Global Map of Irrigation Areas v5 for 2005. Orography over 600m is shaded grey.

Furthermore, moisture recycled from the IGP has been shown as the source of intense rainfall for the 2010 Pakistan floods (Martius et al., 2013). Many operational models do not explicitly incorporate irrigation (Wei et al., 2012), a factor likely to degrade model predictive skill, across India and the IGP in particular (Saeed et al., 2009). Moreover, a recent study has shown that whilst large-scale models tend to favour a positive local feedback between soil moisture and afternoon precipitation, observations point towards a feedback of opposite sign

(Taylor et al., 2012). In semi-arid regions, mesoscale surface flux contrasts can substantially influence the initiation of deep convection (e.g. Taylor et al., 2011). **The impact of the historical**

and continuing expansion of irrigation on the life cycle of convective systems across northern India remains an open question and one which may affect key aspects (e.g. monsoon onset). More data on surface characterisation and its interaction with the boundary layer is needed to understand mechanisms involved in the diurnal cycle and the life cycle of convective systems.

Convection is parametrized in global models and they thus struggle to capture the distribution, structure and timing of tropical rain (Stephens et al., 2010). Deep convection is a key component of the tropical mean flow and failure to represent convection adequately has impacts beyond rainfall, affecting the entire monsoon flow (e.g. Marsham et al., 2013 for West Africa). Increased computing power finally allows this long-standing problem to be addressed; with continental-scale convection-permitting runs now cheap enough to be run for entire seasons. We now therefore urgently require the detailed observational datasets to evaluate such runs, allowing us **to determine the role of convection in the monsoon, and in models the effects of resolution and parametrization.**

Synoptic variability is connected via scale-interactions to boreal summer intraseasonal variability (BSISV), with its inherent northward propagation manifesting as *active* and *break* events over India during the monsoon, which explain much of the variance during summer on 30-60 day time scales. These features are poorly represented in models (Sperber & Annamalai, 2008), although CMIP5 integrations now show northward propagating signals (Sabeerali et al., 2013). SST forcing and ocean coupling is thought to be important for northward propagation and models certainly show sensitivity to its utilization (Klingaman et al., 2011) but recent work has also suggested the potential role for the land surface in this propagation (Bollasina and Ming, 2013). In order to model these aspects correctly and thus improve monsoon prediction at these scales, there is an urgent need to **understand the relative roles played by the land and ocean surfaces during the onset and propagation of modes of variability.**

It has been argued that models need to be able to represent the mean state and full spectrum of monsoon variability for us to have confidence in their future climate projections for the monsoon (Turner & Annamalai, 2012). The biases from small to large-scale motivate further study in the development of the monsoon, its progression and synoptic systems as a way to understand their causes. Recent model comparison exercises such as metric analysis in CMIP5 (Sperber et al., 2013), or the more in-depth work undertaken by the UoR/Met Office Monsoon Working Group, attempt to identify the processes involved in model biases. However there is a paucity of available observations and a recent view suggests that current observations do not provide enough constraint for coupled GCMs for India (Collins et al., 2013). Assimilating new observed data of the atmosphere has been shown for other regions to add value to model analyses and forecasts (e.g. Aberson, 2003). Surface fluxes are poorly constrained and irrigation is poorly described for India. These factors may limit the ability of NWP and seasonal forecasting models for India and contribute to perceived lack of predictability from land surface initialisation in the tropics (e.g., Koster et al., 2011). Through better provision of data, we will therefore be able to further interrogate our models on a range of scales, from the formation of convection over land, ocean and orography, interactions with the boundary layer and larger scale.

These critical gaps in knowledge and predictive tools motivate the following questions to be answered during this project:

- Q1. How are the characteristics of monsoon rainfall on sub-daily to intraseasonal time scales influenced by surface, thermodynamic and dynamic forcing, as monsoon air moves from the ocean inland and across the subcontinent?
- Q2. How do land surface properties interact with the monsoon on hourly to monthly time scales and from kilometre to continental spatial scales?
- Q3. What is the role of the Indian land surface in the progression of the monsoon during the onset and in the monsoon variability, and how can its use aid monsoon prediction?
- Q4. How does convection and boundary layer behaviour on hourly time scales influence rainfall variability on intraseasonal & seasonal time scales, in the real monsoon system and in models?

Specific Objectives

Motivated by the challenges and questions outlined above, the main objective of this project is thus **to improve the skill of rainfall prediction in operational weather & climate models by way of**

better understanding and representation of interactions between the land surface, boundary layer, convection, the large-scale environment and monsoon variability on a range of scales. This yields the following specific objectives to be addressed in work packages:

- 1a) To document and evaluate the characteristics of monsoon rainfall on sub-daily to intraseasonal time scales, as influenced by surface, thermodynamic and dynamic forcing, as monsoon air moves from the ocean inland and across the subcontinent;
- 1b) To evaluate the representation of these rainfall processes in the Met Office Unified Model at a range of resolutions, and thereby to indicate the priorities for model development;
- 2) Characterise land surface properties and fluxes, using in-situ and remote sensing measurements, as they interact with the monsoon on hourly to monthly time scales and from kilometre to continental spatial scales;
- 3a) Quantify the role of the Indian land surface in the progression of the monsoon during the onset, and in the monsoon variability, and relate it to the role of the ocean;
- 3b) Evaluate the impact of improved land-surface representation on monsoon prediction and make recommendations for future land-atmosphere modelling strategy;
- 4a) Evaluate the influence of local and short-term structures in convection and the boundary layer, on rainfall variability on intraseasonal and seasonal time scales, using observations, idealized models and a range of operational models;
- 4b) Make recommendations for priorities in the parametrization of convective rainfall in the monsoon system.

Strategic importance of the work and addressing the scope of the call

The UK Met Office has been working for several years to understand the monsoon dry bias problem (prevalent in state-of-the art models; Sperber et al., 2013), in part through a dedicated in-house process evaluation group (PEG), and through the Monsoon Working Group jointly with PI Turner at UoR. The monsoon simulation and prediction problem is recognized internationally: explicitly mentioned in the *Water Availability and Regional Climate Information Grand Challenges*¹ of the World Climate Research Programme (WCRP). Furthermore, WCRP CLIVAR (Climate Variability and Predictability) has identified monsoon systems as the first of its research opportunities² in which rapid progress can be made over the next 5-10 years. The proposed work will address all aspects of the scope of the call by making process-based observations, including the first campaign using the FAAM aircraft in India; it will entrain new long-term observations, in the form of a network of improved surface flux measurements, to evaluate and improve the JULES land-surface scheme, potentially improving predictability of the South Asian monsoon. The new observations will be brought together with historical data and a hierarchy of modelling work, to develop a more integrated understanding of monsoon processes and improve monsoon prediction. The new flight campaign and intensive observing period will thus build on lessons and understanding from the AMMA campaign in Africa (Parker, Marsham, Taylor) and several campaigns in India (BOBMEX, Bhat et al., 2001; ARMEX, Rao, 2005, and the ongoing CTCZ). By building on existing UK partnerships with India under Changing Water Cycle projects, the MoES National Monsoon Mission, and formal collaborations between the Met Office and NCMRWF, this project will give UK and Indian institutions a leading international role in improved modelling capability for the monsoon.

Research Methodology - Observational campaign

The funding call offers a unique opportunity to invest in an aircraft campaign over India, together with the lasting establishment of new regular surface flux observations at the surface. These benefits will be cemented with a synthesis of existing meteorological data from local Met services as well as existing campaigns such as India's CTCZ³ project and exploiting outputs of AMY⁴, and newfound historical results from ACRE-India. The intended campaign locations are shown in Figure 3, comprising observational transects and other flight paths, a series of upgraded flux towers and high-frequency radiosonde launches.

¹ <http://www.wcrp-climate.org/index.php/grand-challenges>

² <http://www.clivar.org/science/clivar-research-opportunities>

³ Continental Tropical Convergence Zone; <http://www.imd.gov.in/SciencePlanofFDPs/CTCZ%20Science%20Plan.pdf>

⁴ Asian Monsoon Years 2007-2012; <http://www.wcrp-amy.org/index.asp>

The flight campaign transects

The flight campaign and much of the interest in this proposal centres on the heterogeneity across India in terms of the surface and the monsoon as it progresses through onset to maturity. Flight locations have been chosen according to: **a northern-plains transect (NPT)**; **a Western Ghats transect (WGT)**; and **a rain-shadow transect (RST)**, as shown in Fig. 3. The transects are assigned different priorities given the limitations to flying time and fluid nature of aircraft campaigns in response to local logistics and, not least, prevailing weather conditions. NPT contains repeated return paths from Bhubaneswar (our intended main airport base agreed with FAAM, on the northeast coast) to Jodhpur (northwest India), via Patna, Varanasi and Agra in two stages, allowing for a break at Varanasi each time. As shown in Fig. 3, once reaching Patna in the Ganges basin, NPT covers a large-scale transition from the intensive irrigated agriculture of the northern plains to eventually reach the arid Thar Desert in Jodhpur (see Fig. 2). The mean monsoon also undergoes a horizontal gradient from a wet region often under the influence of monsoon depressions in the east, to a dry region of short-lived monsoon coverage in the west (typically not reaching Rajasthan state until mid-July; Fig. 1). This region also hosts the strongest aerosol burdens in India.

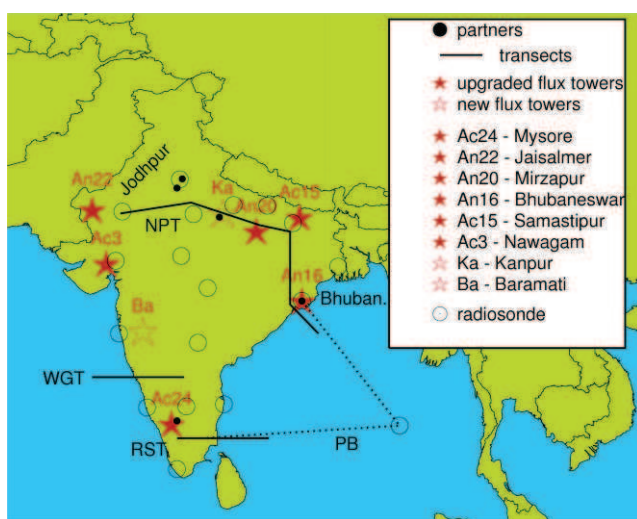


Fig 3. Proposed flight transects NPT, WGT, RST & PB (defined in text); rough positions of partner institutes; 2 new and 6 upgraded flux towers (n=natural; c=cropped vegetation); possible IMD stations identified for additional radiosondes.

Initial ascents from Bhubaneswar will head out over the Bay of Bengal as shown (indicative only) in order to sample the vertical profile of winds and thermodynamic properties and form links with the BoBBLE project also submitted to this call. We will fly the full path to Jodhpur at low-levels to measure surface fluxes and boundary layer properties over irrigated and non-irrigated areas. Once at Jodhpur, specialised flights to determine land-atmosphere coupling will be repeated twice (over two days) departing at around 11am each

day. We will aim to release 40 dropsondes at 1-degree intervals and obtain data from the lidar to provide detail on the atmospheric temperature/humidity profiles and boundary layer structure. A further 8 dropsondes will be used on land-atmosphere coupling flights. The flight back to Bhubaneswar will be taken at low level as far as possible. For WGT we intend to fly from Goa, both eastwards and westwards in order to capture coastal transitions on the land/ocean boundary of the Arabian Sea as well as across orography and across the wet/dry region into the rain shadow. We will use a further 10 dropsondes on this path. In RST we will further sample the rain shadow and land/ocean transitions by flying eastwards from Tiruchirappalli into the southwest Bay of Bengal, using around 6 more dropsondes, before returning. Finally, if planning logistics and cost in time and fuel allows, a long-transect over the Bay of Bengal will be performed, via Port Blair (marked PB). This track will allow overpasses of a ship in the submitted BoBBLE proposal as well as numerous moorings, and will aid study of ocean-atmosphere interaction and provide detailed measurements of the boundary-layer state and atmospheric inflow at the head of the Bay of Bengal, as well as comparison with land surface work. We aim to make use of a triangular circuit of the northern Bay of Bengal from Bhubaneswar suggested in the SWAAMI proposal submitted under this call, a path ideally suited to measuring surface fluxes and boundary layer properties in a region of intense monsoon depression activity and inflow region for the monsoon trough.

Flight times and samples

The evolution of the monsoon necessitates a sample of different conditions to be gathered for the NPT. The proposed campaign with the FAAM aircraft covers around 60 days from mid-May to mid-July, thus encompassing the pre-onset, onset, progression and mature phases of the monsoon. We propose at least three repetitions of the NPT, roughly in mid-May, mid-June and mid-July, estimating a total cost of 20 flight hours per transect. By piggy-backing onto the pre-monsoon pass of NPT in SWAAMI this yields an overall cost of 40 hours. The contrasting mean rainfall and frequency of occurrence for these pre-monsoon, onset and mature phases was shown in Fig. 1.

For WGT and RST the features of interest quickly become fixed during the monsoon (compare the consistent rainfall structure over southern India in the different periods in Fig. 1). Thus we can be more flexible with timing of the transects, operating two samples in late June or July, totalling around 10 hours flying time in addition to the transit time required to fly to and from southern India.

The flux tower network

India currently has a flux tower network consisting of 22 AMS sites where surface fluxes are estimated by the Bowen ratio method. As part of this proposal we will upgrade a targeted set of 6-8 key towers as indicated in Fig. 3 to use the eddy covariance method and install 4-component surface radiometers. This will provide an unprecedented network of surface flux and coincident surface meteorological measurements across India, designed to sample the contrasting surface flux conditions in the region of our transects as shown in Fig. 1 and Fig. 2. Disdrometers are planned at each upgraded tower location for characterizing monsoon rainfall, e.g., convective versus stratiform, and also to ground-truth drop size distributions and Z-R relationships.

Intensive radiosonde launches and other ground-based observation

Selected locations on transects and elsewhere in India will be chosen for launches of radiosondes in order to build on the series of existing twice-daily observations at these IMD stations. We will double the frequency of launches at some stations during the intensive observational period (IOP) of April to August, and double again for portions of the flight campaign period during flying, leading to a frequency of 8 per day and a close estimate of the diurnal cycle. We have requested funding for up to 2400 additional radiosondes for the IOP, and with the help of IMD have determined 20 well-distributed launch stations⁵ as shown in Fig. 3. We aim to be flexible with the space/time distribution of the additional radiosondes during the IOP and aircraft deployment phases, taking heed of local restrictions placed on launches by the Airport Authority of India. In addition, we will have full access to IMD's network of automatic weather stations (AWS, daily), automatic rain gauges (ARG, hourly), satellite products and Doppler Weather Radar (DWR) for the IOP and at least 5 years previously. Further, three microwave radiometers are to be placed in northern India to measure the vertical profiles of temperature and humidity up to 10 km, or give boundary layer scans and measurements of the evolution of CAPE and CIN. These will be based in Bhubaneswar and in two locations in the northern plains, on the northern and southern flanks of the trough.

Modelling work

We will use the Met Office Unified Model (MetUM) that fundamentally uses the same dynamics and physics at all resolutions from NWP to climate scale, in a range of resolutions and configurations. This model is widely used and supported in the UK academic community and is also operated under a formal agreement by NCMRWF in India, who also runs analyses using its version of the model incorporating IMD observations. Using a series of integrations and a nested modelling framework (to be described) we will build on existing partnerships to improve monsoon prediction.

Description of Work Packages

The proposed work is arranged into six packages, four of which cover specific tasks and the other two relate to providing tools and data for the other WPs to deliver science. WP-A provides an organisational backbone to the proposed intensive ground- and aircraft-based field campaign, in addition to managing the project data and dissemination of outputs. As a natural partner to WP-A, WP-B provides the integrated modelling tools and the nested modelling suite for WP1-4. As such, it acts as the modelling counterpart to the observational campaign in WP-A. WP1 uses new and existing data to create an atmospheric characterisation, on short time scales, of monsoon convection and associated synoptic and boundary layer features. WP2 makes use of the new surface flux data, in particular from the upgraded flux towers outlined above, to determine how the surface responds to the monsoon and its evolution. As such WP2 represents a land characterisation and acts as an analogue to WP1. In WP3, we address land-atmosphere coupling, examining how the land surface is affecting monsoon variability on a range of time scales and exploring the potential for improved predictability based on knowledge of the land-surface state. Finally, WP4 examines interactions between convection and the large-scale monsoon and implications for prediction. As shown in the time line of Fig. 4, WP will overlap except in the need to balance planning and set up (particularly for flux tower installation, FAAM campaign management and some modelling work) with adequate time for analysis of campaign outputs. Control of the

⁵Ahmedabad, Aminidevi, Bangalore, Bhopal, Bhubaneswar, Chennai, Gorakhpur, Gwalior, Hyderabad, Jodhpur, Kolkata, Lucknow, Mangalore, Mumbai, Nagpur, New Delhi, Patna, Port Blair (island station), Trivandrum.

overall project, staffing and communication is described in more detail in the attached management plan, while the attached data plan lists the procedures intended for data sharing and output.

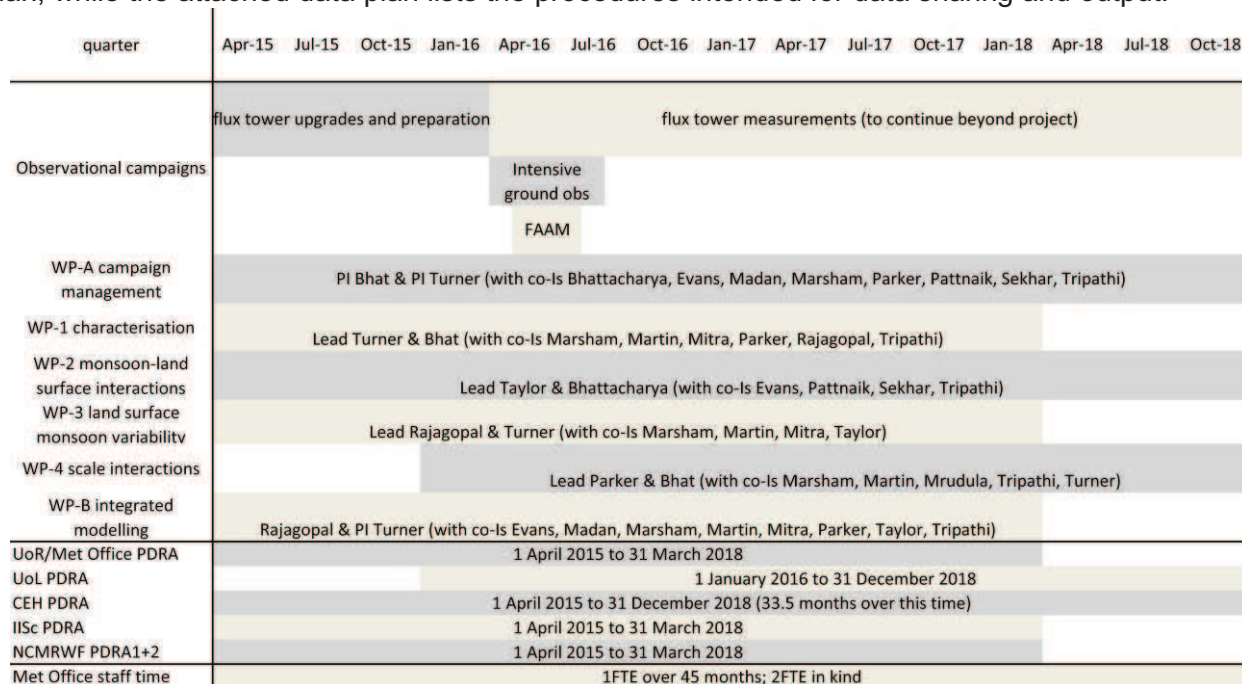


Fig 4. Project timeline. Responsibilities are listed in Management Plan. Times shown for WPs refer to the lead investigators only.

Each WP is listed below with its fundamental aims, key tasks and output deliverables.

WP-A Observational campaign management [Lead IISc & UoR, with CEH, ISRO, UoL, IMD]

WP-A encompasses overall campaign management and provision of observational tools or outputs to the rest of the project. The relative timing of the observational activities and their planning is shown in Fig. 4. Overall charge of the campaign in India lies with IISc (Bhat), with coordination from UoR (Turner) in the UK, in particular for the aircraft campaign. The Met Office will also provide an in-kind contribution of ~4km modelling in support of the field campaign. Acting with our partners in IMD (Madan), WP-A will collate all relevant observed meteorological data under IMD provision, both for the campaign period and the recent historical period, including AWS, ARG, Doppler weather radar and radiosondes. There will be a particular need for focus on the period since 2012 (amounting to 5 years in the campaign year), when NCMRWF started performing analyses and forecasts with their version of the MetUM. Other observed data as in Table 1 will also be collated.

Dataset	Purpose	WPs
Reanalyses products (e.g. ERA-Interim, ERA-Land, GLDAS, MERRA)	Assess veracity of atmospheric conditions in forecasts/hindcasts and long-term mean Compare land surface analyses with depiction in MetUM forecasts	1, 2, 3, 4
Gridded rainfall (CMAP, GPCP, TRMM, APHRODITE, IMD)	Assess veracity of broad-scale rainfall characteristics in MetUM	1, 2, 3, 4
Historical IMD data for period of recent analyses	Determine detailed observed rainfall and atmospheric profiles at the station level	1, 2, 3, 4
NEW IMD station network including radiosondes real-time access during campaign	Comparison with aircraft-derived data, placing the new-high frequency data in context and aiding data assimilation work in hindcasts Comparison of atmosphere vertical structure with that in the MetUM	1, 2, 3, 4
NEW flux tower observations	Challenge land surface models for India with new observations	2, 3
NEW Aircraft and dropsondes data	Very high-density synoptic surveys. Process-based land-atmosphere coupling studies	1, 2, 3, 4

Table 1 – the observational data and its use

New observed data from the campaign and existing IMD data will be mirrored at servers in NCMRWF for India as well as the BADC. The campaign data will span April-August of 2016 for the intensified radiosonde and raingauge and surface meteorological readings and mid-May to mid-July 2016 for the aircraft campaign. We expect new campaign data to be made available to all partners within 3 months of the end of the campaign via BADC. Supported by our partnership between CEH and ISRO, Bhattacharya, assisted by Evans, Sekhar, Pattnaik and Tripathi will coordinate the installation and set up of the upgraded flux towers at 6-8 sites as shown earlier. The expertise and provision of a training workshop in India led by CEH will aid in quality control of these data, to include a cross-site synthesis. Surface flux data from these sites will be available from April 2016-2018. These data will be collected for processing and routine quality control within India, with some limited analyses being done in parallel at CEH to support and guide operations in India. Ultimately quality-controlled flux data will be freely available via CEH's Big Data JASMIN collaboration.

WP-A will also organise annual project meetings for all partners alternating between countries, and offset 6-monthly meetings of UK and India partners separately. Cooperation with other projects under this proposal call is envisaged in arranging the international meetings in order to maximise the outcomes from the coordinated flight campaign.

WP-A deliverables:

D-A1: dataset of existing meteorological observed data for India, IOP data, and collation of meteorological satellite products

D-A2: upgrade flux tower network and provide data

D-A3: collate and mirror FAAM output data

WP-B: Integrated modelling from small-scale convective & land processes to prediction [Lead UoR/NCMRWF with all partners]

WP-B will act as the pathway to improving monsoon prediction through direct connection with NCMRWF/UKMO. This WP features hierarchical modelling servicing all other WPs as a framework for the scientific interpretation of observations. Within WP-B, comparisons will be geared both towards model evaluation and towards understanding model differences and sensitivities. Model-to-model comparisons will look at both what the models produce in terms of rainfall, circulations and convective structures and by what processes they achieve these. Model evaluations against observations will demonstrate whether and which model configurations can simulate some, all or none of what is observed over India. WP-B will therefore act as a vehicle to organise the modelling activity of the other WPs. Tabulated details of model tools to be used are listed below. More information is given in WP1-4. Data transfer of large integrations will be achieved between UK and India, where necessary, by coordinating international project meetings to share hard drives and encourage collaboration. Simple analysis can be achieved by serving limited fields via FTP. Unless otherwise stated in the sub-packages below, modelling will be performed by PDRAs and their investigators as appropriate on national HPC facilities in the UK or India.

WPB.1 Provision of modelling tools and evaluation against observations [as above]

Each WP1-4 will use existing and new observations and model simulations to evaluate model performance in their area of interest. Table 2 shows the range of standard/existing modelling tools available to the project with a brief description of their purpose. These will be used throughout WP1-4 as indicated later and evaluated against observations (Table 1) where appropriate.

Modelling	Purpose	WPs
NCMRWF operational analyses and 1 to 5-day forecasts over a range of years including the IOP	Assess veracity of rainfall and land surface characteristics & change during forecast period(s) Analysis of forecast biases and their relation to GloSea5 climate model biases	1, 2, 3
Global UKMO forecasts	Archive analysis increments to examine development of forecast biases	3, 4
GloSea5 14-year hindcast set & forecast for 2016	Assess veracity of rainfall and land surface characteristics in seasonal hindcasts/forecasts	1, 2, 3
Global 30-year present-day climate simulations at N216, N512 resolutions (AMIP & coupled)	Assess veracity of rainfall and land surface characteristics at typical climate model resolutions	1, 2, 3

Nested suite of EMBRACE simulations for July 2011	Examine rainfall & land-surface characteristics, land-atmosphere and convection-dynamics interactions on range of scales. Explain physics of biases in relation to operational NWP, seasonal and climate runs.	1, 2, 3, 4
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Table 2: Standard/existing model simulations

WPB.2 Model development [UoR, MO, UoL]

As part of the available integrations listed earlier, WP-B will deliver a nested hierarchy of MetUM simulations at a range of resolutions and configurations as outlined in Table 3. This suite of simulations, which is based on the nested suite of EMBRACE simulations listed in Table 2, will be run on a limited domain homing in on South Asia and spanning a range of resolutions from climate through NWP to unprecedented scales for the region. We will include a pair of runs at the same grid spacing (8km), but with convective parametrization and explicit convection, respectively, enabling isolation of issues related to convection parametrization. Evidence in the West African monsoon suggests that the diurnal cycle of precipitation is substantially improved using explicit convection. The land-atmosphere feedback also changes fundamentally, from a positive to negative feedback by switching the convection scheme off (Taylor et al., 2013). This suite of runs will take advantage of on-going developments of boundary layer schemes for high-resolution and “grey-zone” MetUM setups, including a new scheme at the Met Office to blend the standard 1D boundary layer and Smagorinsky schemes. Most of the integrations will follow the methods of and knowledge gained in the EMBRACE project, but using appropriate initial conditions for our observing periods. Models will be initialised with a tracer at the lowest model level; information on its vertical distribution will benefit understanding of boundary layer/free troposphere interaction with the surface. The PDRAs will perform these integrations on the joint Met Office/NERC HPC facility MONSooN. As per our funding request, Stuart Webster of the Met Office will set up the models on MONSooN, while NCAS-CMS will provide assistance in their integration and debugging.

Grid-spacing	Duration	Domain	Moist convection
“climate” 80km	150days	~25x50°	parametrized
20km	150 days	~25x50°	parametrized
8km	150 days	~25x50°	parametrized
8km	150 days	~25x50°	explicit
2.2km	120days	~25x50°	explicit
1km	60days	~25x50°	explicit
~100m	up to 10 days	800x500km	explicit

Table 3: Nested suite of MetUM simulations

As part of the nested suite, we aim to include a limited-area simulation of order 100m resolution. At this resolution we start to emerge from the “grey zone” where the use or otherwise of current convection parametrizations is questionable. In particular, simulations at this resolution should represent entrainment and shallow cumulus phases of convection substantially better than simulations at 1km+ resolutions, and therefore are expected to improve convective diurnal cycles in many areas. It will facilitate better study of convective processes, land/atmosphere interactions on the scale of convective clouds, and convection-dynamics interactions, without the excessive rainfall amounts and local convergence that are usually associated with convection on grid scales greater than or equal to 1km. Building on, and benefiting from, on-going Met Office work at ~100m resolutions in the mid-latitudes, development work in WP-B to explore the benefits of such a limited-area simulation over India will be carried out during the year preceding the observational campaign with work at the Met Office funded by this project. Modelling at this resolution will greatly benefit from further development of cloud and turbulence schemes, requiring dedicated input from parametrization developers at the Met Office to refine and optimise a simulation over India. The tests and development in WP-B of ~100m simulations will let us explore what understanding we may gain from modelling at these resolutions. Based on experience during development of 100m experiments, we will discover the extent to which other sub-kilometre resolutions such as 200m or 500m could be used instead.

WPB.3 Model-to-model comparison & sensitivity tests [UoR, MO, UoL, NCMRWF, NAL, CEH]

Comparisons will be made of land-atmosphere modelling at a range of horizontal resolutions as defined in the nested suite (including those at which convection parametrization can be switched off), with varying parameter values and with updated forcing datasets, to assess the sensitivity of models to these aspects, to refine parameter values and inform future model developments. The final modelling activity in WP-B will be a range of model sensitivity tests as shown in Table 4 and to be performed by the different work packages using the MetUM in a variety of set ups and the JULES land surface model. As such the load will be spread across all partners. The sensitivity tests will exploit the development of a “best-available” set of land boundary conditions for the JULES model (created in WP2.2), which will force MetUM in atmosphere-only and coupled mode.

Modelling	Outline details	Purpose	WPs
NWP modelling	Typically 5-10 day runs at intermediate resolution, changing model parametrizations (e.g., convection, BL)	Examine sensitivity of characteristics of rainfall systems over India and the surrounding oceans to model physics	1
NCMRWF MetUM analyses	Active and break compositing Data denial/OSSE ⁶ experiments	Examination of biases during active and break events Determine value of radiosonde or other measurements to forecast/analyses	1
Point-scale offline JULES modelling	Point runs at flux tower sites forced by observed meteorology	Determine processes responsible for biases in fluxes at various time scales and constrain model parameters	2
Large-scale offline JULES modelling	JULES gridded at 12km resolution	Determine best available radiation and precipitation datasets to force the model Provide multi-year soil moisture and flux analysis	2, 3
Site-specific forecasting (SSF) modelling at flux tower sites	1D-modelling at high vertical resolution	Identification of processes responsible for flux errors leading to refinement of model parameters	2
NWP and climate-scale testing	Short runs based on case studies or 150-day simulations with updated land surface and initialisation Sensitivity tests with fixed/varying soil moisture, land cover/irrigation, roughness, albedo Land and ocean decoupling from atmosphere	Determine role of land surface in shaping observed rainfall events. Effect of land coupling on bias development in atmosphere Understanding land-atmosphere feedbacks and local versus remote drivers; role of the peninsula in the monsoon Role of land and ocean surface in monsoon development and propagation of intraseasonal variability	2, 3
Simple models of scale interactions (NAL)	ODEs generated from diagnostics from the basic nested suite of runs	Understanding scale interactions and feedbacks, including convective/dynamic feedbacks with land surface	2, 4
GloSea5 coupled seasonal forecast system	Case studies of early/late onset years in hindcasts Land surface initialisation tests	Investigate whether model responds to land surface precursors Test benefit of land surface to seasonal forecasting	3

⁶ Observing System Simulation Experiments

Initialised NWP forecasts/hindcasts	Typically 5-day runs corresponding to a synoptic case study or whole-season 150-day runs, using different SSTs	Evaluate ocean-land-atmosphere feedbacks	4
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Table 4: Model studies and sensitivity tests to be performed as part of WP1-4. For brevity, fundamental model assessment work or analysis of the nested suite (as in Table 3) is omitted here.

The remaining WP1-4, making use of observational and modelling work in WPA-B, are next.

WP-1 Synoptic characterisation of the atmospheric thermodynamics and dynamics in observations and models [Lead: UoR/UKMO, with IISc, NCMRWF, IITK, UoL]

To document the monsoon and evaluate its representation in the MetUM, WP1 will characterise rainfall, thermodynamics, surface pressure, boundary layer structure and circulation on sub-daily to intraseasonal time scales over 100m-10000km spatial scales using new and existing observations of the atmosphere, producing new datasets of value to observational and modelling communities.

WP1.1 Atmospheric characterisation across India and adjacent seas [UoR, MO, IISc, UoL, NAL]

Using both existing observations and the new intensive observation transects this characterisation will focus on the changes across the Indian peninsula from the Arabian Sea to the Bay of Bengal. This will be compared with similar analysis of model simulations (including mesoscale analyses and forecasts from NCMRWF coinciding with the new intensive observation transects) at a range of horizontal resolutions, including convection-permitting resolutions from our nested simulations.

We will first examine the synoptic structure of the atmospheric thermodynamics and winds across the whole monsoon system, using radiosondes and airborne surveys, and with a particular focus on the PBL evolution from ocean inland (e.g. through WGT and Bhubaneswar take-offs, analysis as in Turner et al., 2013), and its consequences for convection. We will also examine the intensity, frequency, diurnal distribution and organisation of rainfall as we move along transects (from ocean to land; across orography; across a variety of land surface types). The nested suite of models at a range of resolutions and settings will be evaluated to compare with observed transitions and those in analyses performed by NCMRWF. Finally, we will look at the evolution of biases in composites of active and break phases of monsoon intraseasonal variability in MetUM analyses and model comparison in order to form links with the observed thermodynamics above. This work will establish the extent to which the model at various resolutions captures the convective characteristics on the range of spatial and temporal scales. Data-denial experiments will be performed with the NCMRWF MetUM analysis capability by switching in and out the new observational data (e.g. provided by radiosondes) to determine the added value of new observations to modelling. The data-denial studies may also indicate physical processes that are responsible for biases (e.g. Garcia-Carreras et al., 2013).

WP1.2 Detailed characterisation of the monsoon trough region [UoR, MO, IISc]

As a key source for much of the weather embedded within the monsoon of northern India, we will produce a detailed characterisation of rainfall intensity, variability and organisation in the monsoon trough, and of convective processes within synoptic events/monsoon depressions embedded therein. This will include a range of metrics and more complex diagnostics. WP1.2 will determine the diurnal character and seasonal evolution of the trough making use of the detailed observations of the NPT, the latest ERA-Interim reanalysis and subsequent products, and in comparison with NCMRWF analyses and the nested suite of models. We will determine how the representation of the trough improves with resolution. With the initial supporting involvement of a current UoR/UKMO PhD (started October 2013) we will construct a composite depression, showing its typical evolution, propagation and PBL structure and produce measures of its contribution to total monsoon rainfall in the trough region. This work will particularly focus on data obtained from aircraft sorties in the NPT (proposed in May, June and July) and associated intensive surface measurements including the flux towers and radiosonde launch data.

We will compare the observed composite depression with those in analyses performed by NCMRWF and also in the nested model simulations from WP-B and develop a new series of metrics for analysing monsoon depressions. WP1.2 will determine the role of resolution and convective and boundary layer settings on this phenomenon and establish whether we can hope to resolve dry rainfall biases in CMIP5-class models without improving resolution.

WP1 deliverables:

D-1A: A benchmark dataset and model analyses for the IOP to support future model evaluation, coupled with a paper on the added value of key datasets in model analyses.

D-1B: A pair of papers on the detailed dynamic & thermodynamic synoptic characterisation of the monsoon, model performance and the effect of resolution from climate to sub-kilometre scales.

D-1C: A pair of papers on the monsoon trough and embedded depressions, and the role of resolution in these simulated features, including the effect on systematic dry biases over India.

WP-2 Response of land surface fluxes to the monsoon [Lead: CEH/NCMRWF]

WP2 will characterise the evolution of surface properties and fluxes in response to the monsoon at multiple spatial and temporal scales. In WP2.1 we will exploit new measurements of fluxes and soil moisture across a network of sites including our upgraded flux towers to determine how these fields respond to the monsoon through its development/onset and withdrawal, and how this response varies according to climatic zone (see Fig. 1), land cover and use (e.g. for the distribution of irrigation see Fig. 2). WP2.2 will develop remotely-sensed estimates of key land properties and fluxes for scaling up across the sub-continent. In WP2.3 the JULES land surface model will be evaluated and refined based on comparison with the new in-situ observational datasets. These activities will feed in to a model-based analysis of surface fluxes and states across the Indian sub-continent to provide an estimate of surface flux variability and boundary conditions for the various atmospheric model experiments in WP3.

WP2.1 In situ observations [CEH, ISRO, IISc, IMD, IITB, IITK]

The sampling strategy outlined in WP-A and Fig. 3 will be complemented by access to the data from more than 20 other flux towers. We will provide observed fluxes characteristic of different phases of the annual cycle (pre-monsoon through to post-monsoon dry-down), plus higher frequency variability (dry spells within the monsoon) at a range of irrigated sites.

Comparisons will be made between land surface fluxes estimated from eddy covariance towers and those from the existing micro-meteorological towers in India that are primarily generated using the Bowen Ratio Energy Balance technique. This will include immediately local comparisons at the upgraded towers. Finally, the surface energy balance closure at different sites will be examined.

WP2.2 Large-scale evolution of the land surface [NCMRWF, CEH, IISc, ISRO]

The insight into land surface functioning provided by in-situ data will be complemented by analysis of satellite data and offline regional JULES simulations to build up an understanding of land surface processes at scales up to the sub-continental (e.g. Taylor, 2008). Together with WP2.1 this will generate datasets of flux variability and boundary conditions required elsewhere in the project and available beyond. For the regional offline simulations we will develop multi-year meteorological forcing datasets based on existing methodologies (notably the global 0.5° WATCH Forcing Data / ERA-Interim⁷). For the Indian region, we will develop higher resolution (up to 12 km) variants of the data using gauge and satellite-based rainfall, and explore the utility of satellite-derived radiation data (e.g. ISSCP). The offline simulations will be compared with existing satellite-derived datasets (e.g. soil moisture, evapotranspiration from LandFlux, land surface temperature (LST), terrestrial water storage), and more realistic, satellite-derived descriptions of land cover and vegetation seasonality incorporated into JULES. Near-real-time LST and soil moisture data will also be used to identify transient soil moisture features in support of the aircraft campaign in WP-A.

WP2.3 Land surface model evaluation and calibration using campaign data [NCMRWF, CEH]

This effort will use the outputs of WP2.1 & 2.2 and the campaign outputs of WP-A to assess behaviour of land surface models for India and further develop them. Models will be set up and run for the flux tower sites, forced by in situ and remotely sensed observed meteorological and land cover characteristics. Detailed assessment will allow identification of processes responsible for errors in flux simulations, and on what time scales these errors develop. This will lead to refinement of land surface parametrization schemes and parameter values.

WP2 deliverables:

D-2A: training workshop (India) for set-up, maintenance & analysis of eddy covariance flux towers.

D-2B: paper on the characterisation of surface properties and fluxes through the spatial and temporal evolution of the monsoon.

⁷ http://www.eu-watch.org/data_availability

D-2C: methodological paper on the comparison of Bowen Ratio Energy Balance technique and eddy covariance methods at sites across India.

D-2D: provision of multi-year surface state and flux data from offline JULES simulations to initialise and/or nudge land surface variables within atmospheric simulations in WP3.

D-2E: Feed back of improved parameter values and schemes to our partner Met services UKMO and NCMRWF and associated paper on key processes responsible for flux errors in simulations.

WP-3 Land-atmosphere interactions and the relative role of the ocean [Lead: NCMRWF/UoR, with UoL and UKMO]

To quantify the role of the land surface in monsoon formation, maintenance and subdaily-to-interannual variability, WP3 will use observed case studies from existing in situ and reanalysis data, the new intensive observational campaign (WP-A) and outputs from the integrated modelling work (WP-B), as well as building on the work of WP1-2, to understand fundamentals of monsoon trough structure and the mechanisms behind intraseasonal variability using detailed experiments. To evaluate the impact of improved land-surface representation on monsoon prediction, model runs will test initialised land surface data for all cases and seasons under consideration.

WP3.1 Role of the land surface relative to SST in progression of the monsoon during the onset and in monsoon intraseasonal variability [UoR, NCMRWF, CEH, UKMO]

We will determine the role of the land surface in the development and maintenance of the monsoon trough and in the progression of the monsoon during the onset. This will involve a case study focused on the onset of 2016, occurring during our field campaign and comparisons with long-term observed and reanalysis data. We will generate lifecycles of monsoon intraseasonal variability and composite active/break events including the evolution of land surface fluxes. MetUM experiments will be performed to examine case studies of early and late onset years based on local land-surface and SST precursors, which we will test separately and together. These experiments will help determine the relative role of land and ocean boundary conditions, and of surface characterisation versus continental-scale temperature/pressure gradients and SST on simulation of the monsoon trough. We will draw on outcomes from the BoBBLE project, if funded under this call, to compare measurements of ocean-atmosphere interactions and their impact on the monsoon. In addition we will test the role of the peninsula (building on Turner et al., 2013) and land-atmosphere coupling in propagation of monsoon ISV (vis-à-vis ocean-atmosphere coupling). Experiments using the Met Office coupled seasonal forecasting system GloSea5 will address the role of better land surface initialisation on a 14-year hindcast set to include the campaign year.

WP3.2 Drivers and feedbacks of synoptic and finer-scale activity [CEH, UoR, UoL, MO, NCMRWF]

We will use the new intensive observations to determine the dependence of synoptic features and mesoscale variability on boundary layer stability, thermodynamic and momentum profiles, keeping at the forefront the transitions from ocean to land, wet-to-dry regions and across orography. We will compare these findings with the range of resolutions in the nested suite of models. WP3.2 will determine the role of land surface characteristics in the diurnal distribution of rainfall, and determine statistical relationships between convection and land surface forcing using satellite data. These will include precipitation and cloud, as well as surface soil moisture, land surface temperature and vegetation index. We will use these to evaluate the feedback behaviour of models at different resolutions (e.g. Taylor et al., 2013). High-resolution model composites will be used to quantify synoptic and regional scale feedbacks on the surface state, and we will compare to evaluations of couplings in climate and NWP models at low resolution to determine causes of model bias and offer solutions. The time-step partitioning of model rainfall will also be examined. Finally, parallel analysis of NWP fore/hindcasts with varying initialisation/parameters will benefit process understanding and understanding limitations to modelled monsoon simulations. This will lead to testing of improvements to forecasts of the monsoon on a range of time and space scales.

WP3 deliverables:

D-3A: Quantify role of local land surface characterisation versus larger-scale pressure and SST gradients on simulation of the monsoon trough, with associated paper.

D-3B: Quantify relative role of the land surface to the ocean in northward progression of the monsoon during the onset and in northward propagating ISV, with paper.

D-3C: Inform implications of nested model resolutions and setup choices for prediction through paper on land-atmosphere feedbacks in observations and contribution to synoptic features.

D-3D: Paper on synoptic/regional feed backs to the land surface and causes of biases.
P-3E: Paper on the role of land surface initialisation feeding in to improved seasonal forecasting.
P-3F: Pair of papers on the impact of irrigation and soil moisture on PBL properties based on aircraft case studies and on rainfall based on historical satellite data, respectively.

WP-4 Interactions between convection and the large-scale monsoon [Lead: UoL/IISc, with UoR/UKMO, NAL, IITK]

WP4 will link boundary-layer and convection processes with the dynamics of the monsoon circulations on synoptic and continental scales. We will determine two-way relationships between the various meteorological and dynamical structures controlling the monsoon and its variability. The dynamics of the atmospheric flow lead to spatial scale interactions, with coherent structures such as cold pools, mesoscale vortices and synoptic systems moving energy between the smaller and larger scales. Land-atmosphere interactions cause temporal scale interactions, with the relatively slow evolution of soil moisture (~3 days) providing a low-frequency forcing of the spectrum of convective rainfall. WP4 will evaluate the representation of these various interactions in models of differing resolution and complexity. Our main research tool will be to exploit the suite of nested resolutions of MetUM outlined in WP-B, following the methods of and exploiting data from the Cascade and EMBRACE projects (e.g. Marsham et al., 2013).

WP4.1 Convection and continental-scale coupling [UoL, IISc, NAL, MO, UoR]

In considering the interaction of convection with the mean monsoon state, across the full range of scales addressed by the project, we will determine how individual convective events and the representation of their detailed character at the kilometre-scale impacts the circulation and thermodynamics on the continental scale. Firstly, various measures of the spatial and temporal patterns of convective structure (such as rainfall spectra, composite storm structure, temporal coherence, propagation characteristics) will be used to characterise the convection in model simulations, making use of the broad-brush model evaluations in case study and statistical analysis from WP1.1. Particular attention will be paid to the different convective structures over land and ocean, making use of our observational transects. Secondly, the implications of the modelled storm structures for monsoon scale interactions will be evaluated by diagnosing higher-order measures that cannot easily be observed, such as thermodynamic fluxes and potential vorticity sources, from the model data. We will use methods comparable to those used in the *Cascade* project to analyse convective impacts on the West African monsoon (Marsham et al. 2013), such as the composite analysis of thermodynamic forcing around convective events, as well as statistical analysis of eddy-mean flow characteristics. Together with WP1, this work will build on existing resource, including two CASE PhDs (UoR/UKMO and Leeds/UKMO) both starting October 2013.

WP4.2 Convective rainfall and synoptic systems [NAL, IISc, UoL, MO, UoR]

Following from the composite depression and synoptic system analysis in WP1.2 we will perform an intensive study of the rainfall processes at a variety of resolutions up to the sub-kilometre scale. Feedback between convection, the low-pressure system and the large-scale water budget will be computed, making use of ideas developed in WP4.1 (e.g. the relative roles of cold pools, vortices and land surface in the influence of convection on synoptic scales; NAL-UoL collaboration). From the suite of nested simulations, we will inform how GCMs can better simulate the trough and embedded systems given the large deficient rainfall biases present in these regions. Simple models of the scale interactions will be developed (NAL), and quantified directly against the model and observational results: for instance we will consider models of convective-dynamic feedbacks with the land surface state, in which the diurnal cycle of convection interacts with lower frequency variability of the surface and the monsoon dynamics (e.g. Parker 2008).

WP4.3 Scale interactions in the water cycle [UoL, MO]

In the nested suite of simulations, we will evaluate the various terms controlling the water cycle of the monsoon, separating the spatial and temporal scales as in WP4.1 (see Meynadier et al. 2010, Birch et al. 2014). From these results, benchmarked against the observations of WP1, we will evaluate the impacts of convective parametrizations on the water budgets. Finally, the water budgets of UM NWP analyses, forecasts and climate model simulations will be compared to the observations and high-resolution models, to isolate the structures of “fast” causes of forecast biases (notably due to convection, and developing over 1-2 days, e.g. Rodwell and Palmer 2007; Birch et al. 2014), relative to slower biases (e.g. SST-forced biases).

WP4 deliverables:

D-4A: Document impact of individual convective events and representation of their detailed character on the circulation and thermodynamics at the continental scale.

D-4B: paper on simple models linking convection and dynamics.

D-4C: paper on feedback between convection, low-pressure systems and large-scale water budget

D-4D: paper isolating fast and slowly developing forecast biases in a range of simulations

Improving predictions

The major benefit of this project will be improvements made to monsoon predictions on a variety of spatial and temporal scales. By comparing our measurements of monsoon processes generated from the observational work in WP-A and the extensive modelling work in WP-B we will ensure that we can both assess models in ways previously not possible and improve them. WP1 will directly support detailed synoptic characterisation of the monsoon and provide new data for model assessment. WP2 will yield new datasets of the land surface with which to force models and better initialise monsoon forecasts, as well as addressing the key biases in land surface models. The effect of the land surface on the monsoon and its modes of variability in a variety of forecasts in WP3, including the synoptic, seasonal and climate scales highlighted in India's National Monsoon Mission, will address the role of the land surface in monsoon forecast biases and ensure direct feed through of the improved process understanding into monsoon simulation. Finally, WP4 will harness the connections between convective and land processes and the larger-scale monsoon and improve predictability by separating slow and fast developing forecast biases.

Risk and reward

The improved predictive capability in the land-monsoon system that this project will offer in the medium term comes with risks. There are inherent political, technical and weather risks in aircraft detachments, but we have the time (60 days) allowing for considerable flexibility. The opportunity offered by a FAAM detachment to India will ensure that any measurements made will be useful, and the experience of our partners suggests that when such unique high-quality data are available, even a small number of flights can yield substantial scientific progress. Little risk is offered in the IOP of weather station observations and enhanced radiosonde launches since with IMD we can maintain flexibility according to changes in science rationale. The network of flux tower upgrades, requiring considerable logistics, potentially yields large benefits in terms of a long-term new dataset for India. Even a little input from experts at CEH on siting and operation will yield big impacts. Risks are minimised by building on the existing AMS network of infrastructure and support. At the high-resolution limit of our modelling, difficulties may be encountered in producing optimally-configured simulations at the 100m scale for India. However even if a specific ~100m integration is not delivered, considerable improvement in understanding the limitations of model parametrizations and modelling at coarser grid scales will be achieved. In addition, advances will have been made in Indo-UK modelling capability in order to compete with other international groups, strengthening ties between the Met Office and its academic partners.

Role of the Met Office

As part of an academic partnership with UoR and UoL, the MO and its MetUM model (also used at NCMRWF) are central to this project. Skills held at MO in parametrization and model design are essential to development work of credible sub-km scale models for an Indian domain that will allow us to push the boundaries of atmospheric modelling towards scales emerging from the "grey zone". This will build on experimental work being done at the Met Office for mid-latitude regions, which has demonstrated that careful consideration of model design and parameters is required in order to achieve useful model results at such resolutions. Aspects of the project in which we gain better understanding of the causes of land surface and atmospheric biases, through our JULES modelling work and field campaign, will feed directly into MO for improvements to parametrizations.

Collaboration with other proposals under the call

The unique funding opportunity offered may allow pursuance of up to three projects, the others being SWAAMI (targeted at monsoon-aerosol interactions) and BoBBLE (ocean-atmosphere interactions and mixed layer processes in the Bay of Bengal). For the former, our choice of northern plains transect coincides with the key area of high emissions and aerosol loading in South Asia. The choice of sampling strategy for the NPT covers the middle of May, June and July, allowing for a contrast of aerosol and climatological conditions. PI Turner is already involved with a SWAAMI co-I (Highwood) in a Changing Water Cycle project examining aerosol-modelling work for India. We anticipate sharing data from flight campaigns and atmospheric structure. PI Turner is a

project partner on the BoBBLE proposal, while PI Bhat is a co-I there. Clear benefits of working together allow us to contrast the effects of ocean-atmosphere versus land-atmosphere coupling (see Letter of Support). In addition, the flight route RST will allow us samples of land-ocean contrasts in surface fluxes and thermodynamic profiles of the atmosphere, as well as sampling of the oceanic part of the rain shadow extending from southeast India (see Fig. 1).

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