Part 2: Projected Responses of Extreme Precipitation and Atmospheric Radiative Energy (PREPARE)

Projected increases in the amount and intensity of rainfall and the coverage of regions experiencing drought will lead to adverse impacts on societies, agriculture and health. An emerging body of evidence indicates that climate models may be underestimating current changes in the global water cycle. It is crucial that the causes of discrepancies between simulated and observed responses of the atmospheric hydrological cycle are identified and urgently addressed. The current proposal seeks to tackle this serious issue by testing the following hypotheses:

Hypothesis 1: Monitoring changes in the global water cycle is limited by the observing system;

Hypothesis 2: Present day changes in the Earth's energy balance relating to aerosol are currently influencing trends in the hydrological cycle;

Hypothesis 3: Spatial resolution and physical parametrizations employed in current climate models are inadequate for simulating present day changes in the global water cycle.

These questions will be addressed by combining high quality satellite and ground-based observations of the Earth's energy and water budgets, bringing together important lines of research and collaborators with unique expertise in climate change, the Earth's radiation budget and the hydrological cycle. The results will enable more rigorous assessment of the implications for projected future changes in rainfall and its extremes, a key goal of the new program on changes in the water cycle announced in the NERC strategy, Next Generation Science for Planet Earth and central to the NERC Climate system theme and National Centre for Earth Observation (NCEO) and Reading's Walker Institute for Climate System Research.

Scientific Rationale

Understanding the regional response in the hydrological cycle is crucial in planning for and adapting to climate change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change states that substantial changes in the global water cycle are expected in the current century in response to projected global warming (IPCC, 2007). It has long been known that the Earth's energy and water cycles are intrinsically coupled (Mitchell et al. 1987) and there exists a balance in the atmosphere and at the surface between the net radiation budget and the turbulent heat flux exchanges including latent and sensible heat fluxes (Figure 1; Trenberth et al. 2008). The latent heating is a particularly large component and involves evapotranspiration at the surface and condensation in the atmosphere and eventual precipitation. Thus the water cycle transfers heat acquired through radiative absorption at the surface to the atmosphere as part of a radiative-convective equilibrium. Thus it is reasonable to expect that changes in the radiative flows of energy will exert a corresponding change in the latent heat fluxes and ultimately the global water cycle.

Climate models have long predicted changes in the global water cycle in response to greenhouse gas forcing (Mitchell et al. 1987) with projected increases in precipitation scaling with global warming (Held and Soden 2006). Yet detecting such changes in observational datasets has, until recently, been elusive. Current climate models project not only increases in global precipitation but an intensification of the heaviest rain events and an enhancement of the areal coverage of drought regions, with corresponding adverse effects upon agriculture, soil quality, human health and infrastructure (IPCC, 2007). Positive trends in precipitation and evaporation from satellite data are beginning to be detected (Wentz et al. 2007) suggesting that these changes are already under-way. Evidence from satellite data (Allan and Soden, 2008) and ground-based records (Lenderink & van Meijgaard, 2008) also appears to corroborate model projections of an intensification of the heaviest rainfall events. However, precipitation response is not spatially uniform; surface records indicate contrasting responses across different latitudinal zones (Zhang et al. 2007) and indications that wet regions will become wetter at the expense of the already dry regions is a robust result across climate models (Held and Soden 2006) and is supported by contrasting precipitation trends across ascending and descending branches of the tropical circulation (Allan and Soden, 2007) and between the wet and dry seasons (Chou et al. 2007).

While ground-based and satellite data appear to corroborate, in a broad sense, model projections of wet regions becoming wetter and dry regions drier, an emerging body of evidence suggests that simulations by state-of-the-art climate models are underestimating the response of the hydrological cycle to warming (Wild et al. 2004; Zhang et al. 2007; Wentz et al. 2007; Chou et al. 2007; Roderick et al. 2007; Allan and Soden 2007, 2008) and it is vital that the reasons for this discrepancy are rapidly elucidated.

To address this outstanding and important issue, an appreciation for the root causes of changes in rainfall is required. Evidence from sophisticated climate models and observations from a variety of sensors point to robust increases in atmospheric moisture with warming at about the rate expected from physical theory (around 7% per K warming; Held and Soden 2006). Rising moisture fuels intensification of the heaviest rainfall events (Trenberth et al., 2003). This, however, is not the full story: global precipitation is intrinsically linked to Earth's atmospheric energy budget. The relatively slow rises in atmospheric net radiative cooling, as the planet warms, can only support modest rises in latent heating through precipitation of around 1-3% per K, much slower than the rises in heavy rainfall (Allen and Ingram, 2002). This leads to a reduction in rainfall away from convective regimes. While both climate models and satellite observations indicate that dry regions are becoming drier and wet regions wetter, further comparison suggests that models underestimate this response when considering these regions separately (Figure 1; Allan and Soden, 2007).

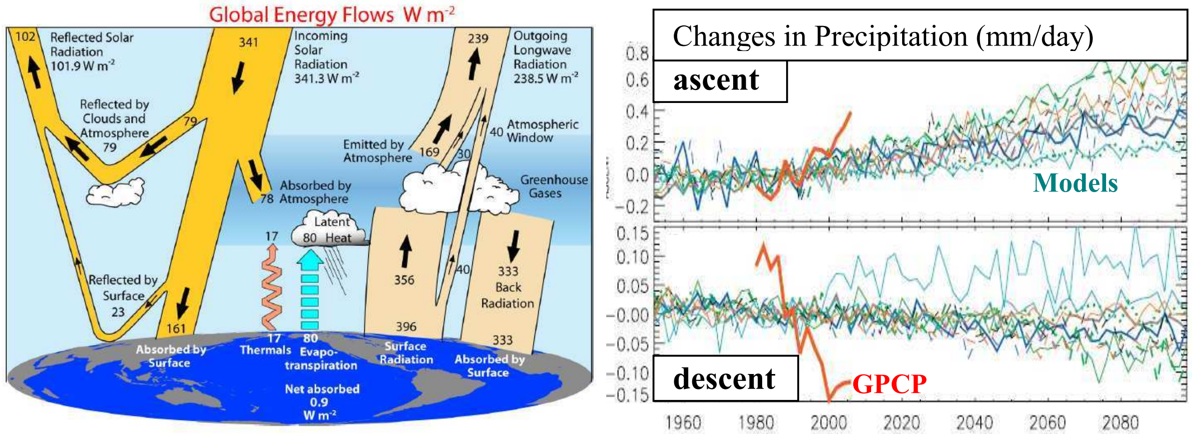

Figure 1: *The global energy balance (left; Trenberth et al. 2008) linking radiative energy fluxes with turbulent energy fluxes through latent and sensible heat and (right) the discrepancy between observed and simulated present day changes in precipitation in the ascending and descending branches of the tropical circulation, in the context of the future projections to 2100.*

To understand the reasons for the important discrepancy between models and data, we bring together important areas of expertise in the Earth's energy balance and the Global water cycle. The three main approaches are to (i) monitor, (ii) inter-compare and (iii) understand and predict changes in the hydrological cycle. These can be achieved by employing a unique combination of satellite and surface-based measurements of precipitation, evaporation and the Earth's radiative energy balance. Inter-comparison of existing and new satellite datasets will allow improved monitoring of changes in key variables such as precipitation and evaporation. Combining the hydrological and radiative components of the energy and water balance in models and observations will enable a better understanding of the physical processes involved and improve estimates of changes in the surface radiation budget. Carefully constructed model experiments will explore the impact of changes in aerosol on the hydrological cycle through radiative forcings. The results will be paramount in improving estimates of future impacts from changes in the hydrological cycle on societies and ecosystems.

One plausible hypothesis to explain decadal responses in the water cycle is that changes in aerosol (Wild et al. 2005; Mischenko et al. 2006) have exerted a significant effect on the surface and atmospheric radiation balance (Wielicki et al 2002) effectively "short-circuiting" the global water cycle (Ramanathan et al. 2005). Inadequacies in the models and the satellite datasets may also contribute to the discrepancy. A primary goal of this proposal is to assess whether inadequacies in models or the satellite datasets can explain the discrepancy or whether changes in aerosol and/or cloud are driving decadal responses in the atmospheric hydrological cycle. The implications for future projections of rainfall and its intensity will be of vital importance in preparing for climate change; for example the hydrology community requires detailed information on how distribution and return periods of rainfall events will respond in a warming world (Arnell et al. 1990).

Scientific Objectives

The primary goal of the project is to understand and address the sources of discrepancy between observed and model simulated responses of the global water cycle and energy balance to warming, thereby improving confidence in climate projections including rainfall extremes. This is of relevance both to the UK and international community (IPCC, GEWEX) interested in predicting and planning for changes in climate and the water cycle, a key objective of the NERC strategy. Specific objectives are:

Objective 1: Inter-compare datasets encapsulating key aspects of the hydrological cycle and energy balance and identify most suitable products for representing decadal or long-term changes;

Objective 2: Construct an improved representation of long-term changes in the surface energy budget using satellite data, empirical models and ground-based measurements, thereby providing independent constraints on changes in the global water cycle. Make available the resulting dataset;

Objective 3: Detect and monitor current trends in precipitation, evaporation and the radiative energy balance using dynamical regime analysis and identify limitations of satellite and ground-based observations;

Objective 4: Identify inadequacies in model simulations of changes in mean/extreme precipitation, evaporation and the surface and atmospheric energy balance relating to model physics/resolution;

Objective 5: Evaluate model projections of changes in precipitation extremes utilising new daily satellite data and combining with dynamical fields from reanalyses;

Objective 6: Quantify the influence of changes in surface temperature, greenhouse gas concentrations and aerosol properties on present day changes in the global water cycle through modelling experiments;

These objectives will be met through the work packages detailed in the next section.

Dataset	**Variable**	**Period**
Clouds and the Earth's Radiant Energy System (CERES); Earth Radiation Budget Satellite (ERBS)	Top of atmosphere radiative fluxes	2000-present; 1985-1999;
International Satellite Cloud Climatology Project (ISCCP); GEWEX Surface Radiation Budget (SRB); CERES derived surface fluxes	Surface and top of atmosphere radiative fluxes and clouds	1983-present; 1983-present; 2000-present
Baseline Surface Radiation Network (BSRN); Global Energy Balance Archive (GEBA)	Surface radiative fluxes	1990-present; 1960s-present
Special Sensor Microwave Radiometer/Imager (SSM/I)	Column water vapour, Wind Speed, Precipitation, Liquid Water Path (daily/monthly)	1987-present
Woods Hole Ocean-Atmosphere Fluxes (OAFLUX)	Surface Evaporation (oceans)	1983-present
Global Precipitation Climatology Project (GPCP)	Precipitation	1979-present
Global Precipitation Climatology Centre (GPCC)	Precipitation	1986-2000
Reanalyses (NCEP, ERA40, ERA Interim)	Water vapour, Temperature, Vertical Motion, Clear-sky radiation, Evaporation	1979-present
Tropical Rainfall Measurement Mission (TRMM)	Precipitation	1997-present

Table 1: details of PREPARE core datasets, variables and time-spans

Methodology

WP1: Development of PREPARE core datasets

Building on considerable experience with satellite, reanalysis and ground-based products key to understanding changes in the hydrological cycle, this work-package will finalise the core datasets for use in the remaining work packages (see Table 1). This will involve assessing the strengths and weaknesses of each data type, concentrating inter-comparisons of (i) climatology, (ii) seasonal cycle and (iii) inter-annual variability. Since changes in atmospheric net radiation provide a powerful constraint upon precipitation changes (Allen and Ingram, 2002; Lambert and Webb, 2008), a major focus of the project is to bring together the most stable, well calibrated estimates of radiative and latent heat fluxes. Continuous updates of datasets will enable monitoring of the water cycle during the project. In addition to consolidating existing datasets and acquiring new products listed in Table 1, the most resource extensive aspects of this work package are as follows:

1) Acquire and assess monthly and daily precipitation data from the Tropical Rainfall Measurement Mission (TRMM) and the Global Precipitation Climatology Centre (GPCC) [with Partner 1]

Utilising the experience of Project Partner 1, the feasibility of exploiting recent products from TRMM and GPCC for analysing inter-annual changes in precipitation and precipitation extremes will be investigated. Inter-comparison and enhancement with existing and new datasets, including the use of high density rain-gauge datasets over Europe and the UK, will allow full utilization in WP2-3 for quantifying uncertainty in present day responses of precipitation to temperature and moisture and assessing the range of rainfall-temperature relationships (e.g. Wang et al. 2008).

2) Processing of ground-based radiation data from the Baseline Surface Radiation Network (BSRN) and development of an enhanced surface radiation dataset [With Partner 2]

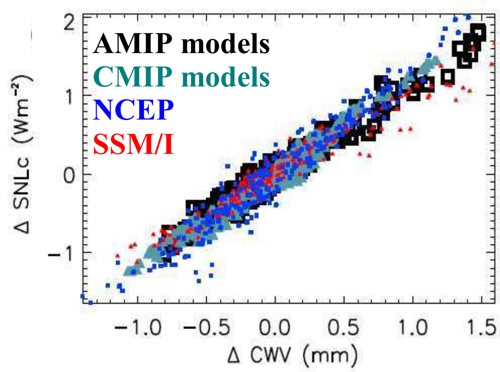

Figure 2: *Clear-sky Surface Net-down Longwave radiation (SNLc) and column integrated water vapour (CWV) in models, reanalyses and SSM/I data.*

One of the least well sampled components of the Earth's Radiation Budget is the surface downward longwave radiation (SDL) (Trenberth et al. 2008; Wild et al. 2008). Therefore considerable care will be taken, as part of PREPARE, to ensure that this crucial flux is well sampled. While global gridded radiation products, derived from satellite data, are available (ISCCP-FD, SRB, reanalyses), decadal changes from these datasets are questionable (Evan et al. 2007; Allan, 2007). A methodology will be developed to combine the BSRN/GEBA data with existing gridded products (ISCCP-FD) and estimates derived from additional satellite data (SSM/I) to generate an enhanced product for representing changes in the surface energy budget. The most robust determinant of SDL variation is the column integrated water vapour (CWV) (see Figure 2). SSM/I products provide the best record of decadal changes in CWV (Trenberth et al. 2005); these data will be used along with the method employed in Allan (2006) to first derive clear-sky SDL (SDLc) over the ocean,

$$\mathrm{SDLc} = \left\{1 - (1+u)\exp\left[-(1.2+3u)^{\frac{1}{2}}\right]\right\}\sigma T_0^4, \qquad (1)$$

where u=CWV/10 and T_0 is the near-surface temperature. The Post-Doctoral Research Assistant (PDRA) will develop this semi-empirical model (Prata, 2008), using additional information from the CERES/ISCCP datasets, to include the effect of cloud, aerosol and greenhouse gases, all second order effects over the tropical oceans. This is a research problem and particularly suited to detailed investigation at the University of Reading, the results of which will be valuable in model evaluation of surface fluxes, a neglected practice until recently (Bodas-Salcedo et al. 2008; Wild, 2008). The culmination of this work package will be to provide a representation of inter-annual to decadal changes in the surface radiation budget and the hydrological cycle, including precipitation and evaporation, meeting objectives 1 and 2.

WP2: Quantify Trends and Physical Relationships

Using the core PREPARE datasets, interannual variability in the radiation budget and hydrological cycle and responses to surface temperature and CWV will be quantified and compared with models from the CMIP3 climate model archive. A particular question to address is how sensitive are the observed relationships with temperature and moisture when considering (i) differing regions (ii) contrasting time-periods and (iii) alternative datasets. Figure 3 suggests a large spread in precipitation variability when considering a variety of precipitation estimates.

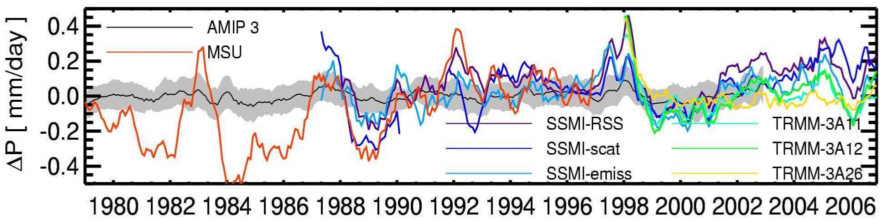

Figure 3: *Tropical precipitation variability from satellite data and AMIP3 climate models*

Specifically, the sensitivity of precipitation changes to changes in surface temperature and CWV will be calculated, using linear regression, for the tropics and extra-tropics and for ascending and descending regimes. It will be important to establish whether contrasting precipitation response in the wet and dry regions of the tropics (Allan and Soden, 2007) is a robust result and whether differences between observations and models are within the inter-dataset uncertainty range. It is anticipated that a high-profile publication can be prepared relatively rapidly on this analysis.

WP3: Improved Projections of Precipitation Extremes

Increases in the intensity of the heaviest precipitation with warming are beginning to be detected by satellite (Allan and Soden, 2008) and ground based measurements (Goswami et al. 2006; Lenderink and van Meijgaard, 2008), helping to corroborate projected future changes by models (Semenov and Bengtsson 2002). However, there remain discrepancies between climate models and satellite estimates of observed changes in precipitation frequency over the ocean in response to present day warming and cooling cycles (Figure 4). The work package will be sub-divided into three key stages:

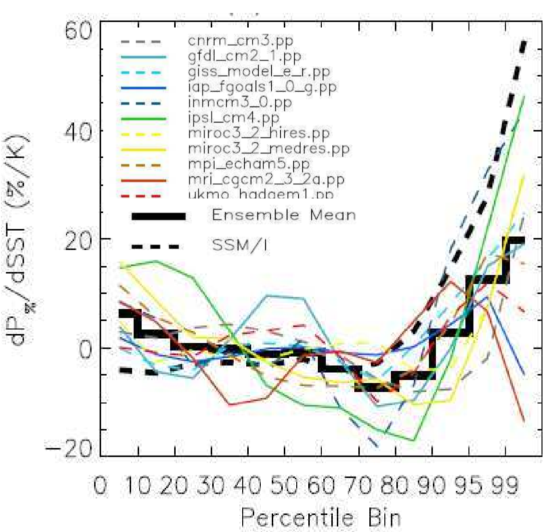

Figure 4: *Frequency of precipitation intensity response to surface temperature from SSM/I observations and climate model simulations.*

Stage 1: Analysis of precipitation extremes will be extended to include land and higher latitudes, using the most up to date SSM/I retrievals and new GPCP daily data. Specifically, how does the frequency and magnitude of the heaviest and lightest precipitation events respond to warming over different regions? The probability distribution of precipitation events will be calculated, in both frequency and magnitude space. Linear relationships with local and large-scale temperature and moisture will be calculated (Fig. 4) to assess how precipitation extremes respond to warming relating to natural variability and trends.

Stage 2: Daily rainfall totals from TRMM and high density surface gauge networks over Europe and the UK will be utilized and compared with responses from coupled model simulations and SSM/I data, answering the question, how sensitive are the observed responses to different time-periods and to independent datasets.

Stage 3: The final component of the work package will be to bring together previous analysis (Bony et al. 2006; Allan and Soden 2007,2008) by sampling changes in extreme precipitation, sub-sampled by dynamical regime. To do this, daily precipitation data will be sampled in terms of monthly or pentad vertical motion bins from reanalyses (ERA40 and Interim reanalyses; Uppala et al. 2005), thus assessing how different rainfall intensity changes in the present day climate depending upon the degree of ascent or descent and including rainfall intensity within tropical cyclones (Bengtsson et al. 2007). The locations that are primarily affected by changing precipitation extremes will be identified in models and satellite data, thereby providing information pertinent to adaptation strategies. Model data will be extracted from the PCMDI CMIP3 archive. Given the large quantities of data, existing Unix scripts will process one model at a time, storing the results locally. A published paper will be the primary deliverable of this work package.

WP4: Modelling Experiments

In collaboration with the Met Office partners, we will investigate the effects of changes in surface temperature, greenhouse gases and aerosol changes on the surface and atmospheric radiation balance and the atmospheric hydrological cycle, including latent and sensible heat fluxes. The results of the model experiments will be compared with the core PREPARE datasets, including analysis of changes in precipitation and extreme events. The experiments will consist of:

1) *Control involving prescribed Sea Surface Temperature (SST) changes*
2) *Control plus greenhouse gas increases*
3) *Control plus aerosol changes*
4) *Control plus aerosol changes multiplied by 4*
5) *Control plus greenhouse gas and aerosol changes*

Each experiment will consist of four ensemble members, beginning from differing initial conditions, and run over the period 1979-2008 using observed SSTs. Ideally, existing integrations will be utilized although it is likely that Scenario 4 will require the creation of a new experiment. Corresponding coupled model experiments will be valuable in interpreting the causes and impacts of changes in the radiation and water balances. Existing integrations will be utilized; resources for running new coupled model experiments are not deemed necessary.

The output will be analysed using a methodology consistent with that applied to the observational datasets, as detailed in WP1-3, quantifying the variability and responses to temperature and water vapour regionally and stratified by vertical motion bins. The effects of implementing modified convection and boundary layer schemes on the responses of precipitation to surface temperature will be assessed using pre-existing runs from HadGEM2 or the developmental model version HadGEM3. To test the influence of model resolution, data from the HiGEM project will be exploited. The results of these experiments will provide an important source of knowledge exchange with the Met Office and be of use in development of the newest climate model version, HadGEM3, in addition to disseminating information via the IPCC process through the final work package.

WP5: Implications for Climate Projections

The results from the previous work packages will provide the foundation for assessing predictions of future changes in the hydrological cycle and implications for climate adaption strategies. Is the accuracy of such projections limited by (i) the observing system, (ii) uncertainty in the forcing prescribed in simulations or (iii) limitations in the feedbacks represented by physical processes parametrized in models? Also, can monitoring of the present day changes in the hydrological cycle provide timely information on the uncertainty and the magnitude of expected future changes in the coverage of severe drought, intense rainfall events and cloud feedback (Andrews & Forster, 2008).

The purpose of this work-package is two-fold: to direct the focus of the previous work packages toward delivering information pertinent to improving future climate predictions and adaptation strategies and to distil the results and disseminate the conclusions to the community through publications and knowledge transfer to the Met Office, to society through lectures and outreach and to policy makers through NERC, the Hadley Centre and the IPCC. A special session will be organised at the AGU meeting during the final year of the project. Interaction with complimentary programs will be explored, for example utilizing results from the High resolution Global Environmental Modelling (HiGEM) project to study the effects of space resolution on the responses of the hydrological cycle, and the NERC programs, Aerosol Properties, PRocesses And InfluenceS on the Earth's climate (APPRAISE) and Surface-Ocean / Lower Atmosphere Study (SOLAS).

Deliverables

D1: A paper detailing inter-comparisons of datasets and the development of an enhanced surface radiation budget dataset for use by the community (WP1).
D2: A concise, high-impact paper detailing agreement and inconsistencies amongst datasets and models in representing relationships between precipitation, temperature and moisture (WP2).
D3: The culmination of WP2-4, a substantial publication will detail changes in the global radiation and water balance in present day observations and model simulations and future projections.
D4: Disseminate conclusions of D1-3, outlined in WP5 to the climate change community, the hydrology community, policy makers including the IPCC and government agencies such as the Met Office and Environment Agency and to the public. These will be achieved through outreach activities, a range of publications and meetings and workshops including a special AGU session.

Project Management and Wider Application

Richard Allan (University of Reading) takes overall responsibility for the management of the project. The project will primarily utilize existing resources at the University of Reading to store and process PREPARE core datasets. Partner 2 (ETH Zurich) will provide data and expertise regarding surface radiation and Partner 1 (Met Office) will supply model data and perform, where required, additional simulations. A full plan of activity is included in Table 1.

	2009	2010				2011				2012		
WP1					D1							
WP2										D3		
WP3						D2						
WP4												
WP5												D4
PARTNER 1												
PARTNER 2												

Table 1: *Plan of work packages and timing of deliverables and Project Partner contributions*

All partners, including the PDRA and Co-Investigator (Prof. Bengtsson), will contribute to deliverables, through publication in high impact, peer-reviewed journals, and dissemination through workshops, conferences, and outreach. The development of an enhanced, gridded surface radiation budget dataset and the capability for ongoing monitoring of changes in the hydrological cycle will be a legacy of the project, and available for wider NCEO activities. The project will present considerable training opportunities for the PDRA, working in an important and fast-moving area of research, developing expertise in processing large datasets from satellite and ground-based instruments and climate models with the opportunity to apply communication skills both to peers and policy makers. The interaction with the Met Office Hadley Centre and the availability of an extensive staff training and development program at the University of Reading will be valuable for career development.

Existing collaborations with the University of Miami, the PP Shirshov Institute of Oceanology (Moscow) and the Lamont-Doherty Earth Observatory of Columbia University (New York) will aid the PREPARE project as will a central position within the NERC Centre for Earth Observation (NCEO), the NERC/Met Office Joint Climate Research Program (JCRP) and Reading’s Walker Institute. Collaboration will be sought with the hydrology community, including the NERC Centre for Ecology and Hydrology, in view of utilising high density rain-gauge network across the UK and Europe. Links will be sought with existing NERC programs, dealing with the effect of model spatial resolution (HiGEM), prescription of aerosol forcings (APPRAISE) and sensitivity to ocean-atmosphere interactions (SOLAS). This will finalise what is an ambitious yet cost effective set of work-packages, achievable in 36 months through expertise delivered by the project partners, and will ensure maximum dissemination of the results. It is vital that serious questions regarding our changing hydrological cycle are met immediately and this is an opportunity for the NERC community to engage with the Met Office to tackle this magnitude problem, ensuring UK science in this area remains at the forefront. The project will tackle the heart of the NERC strategy: it is a proposal with limited risk and will instil integrated research communities and provide UK leadership in monitoring current changes in the hydrological cycle, thereby enabling society to respond urgently to global climate change.

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