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MONITORING CHANGES IN PRECIPITATION AND RADIATIVE ENERGY USING SATELLITE DATA AND CLIMATE MODELS

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Abstract

Current changes in the tropical hydrological cycle, including water vapour and precipitation, are presented over the period 1979-2008 based on a diverse suite of observational datasets and atmosphere-only climate models. Models capture the observed variability in tropical moisture while reanalyses cannot. Observed variability in precipitation is highly dependent upon the satellite instruments employed and only cursory agreement with model simulations, primarily relating to the interannual variability associated with the El Niño Southern Oscillation. All datasets display a positive relationship between precipitation and surface temperature but with a large spread. The tendency for wet, ascending regions to become wetter at the expense of dry, descending regimes is in general reproduced. Finally, the frequency of extreme precipitation is shown to rise with warming in the observations and for the model ensemble mean but with large spread in the model simulations. The influence of the Earth's radiative energy balance in relation to changes in the tropical water cycle are discussed.

INTRODUCTION

Future changes in the global hydrological cycle have profound ramifications for society and the ecosystems upon which they depend upon. Climate model projections of increased global precipitation with warming mask a more complex regional picture, dependent upon changes in the large-scale dynamical circulation but also influenced by large-scale responses of precipitation and evaporation that are a consequence of the thermodynamics and radiative-convective equilibrium maintained by the atmosphere. In considering projections in regional climate it is vital to evaluate and understand the important processes using observations; in the present study we present analysis of variability in water vapour, precipitation and its extremes using a variety of observational products and models and discuss the implications on future projected trends in tropical precipitation.

WATER VAPOUR

Figure 1 shows column integrated water vapour (W) anomalies over the tropical ocean for models (grey shading), microwave observations (blue) and the ECMWF Interim reanalysis (green). Water vapour totals rise in all datasets during warm El Niño years (e.g. 1997/98). However, while the models also capture the observed trends in moisture, the reanalysis instead produces an artificial drying trend, punctuated by discontinuities in the time series. Since water vapour provides a powerful positive feedback to climate warming and it supplies the large-scale and convective rainfall events important in determining the availability of fresh water as well as damaging flooding events, it is important that such variability should be accurately captured by models and carefully evaluated using long-term, stable datasets.

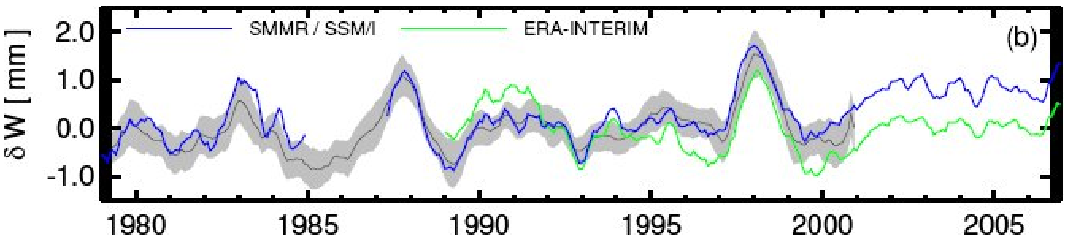


Figure 1: **Tropical ocean deseasonalized anomalies in column integrated water vapour (W).**

PRECIPITATION AND RADIATIVE COOLING

While models reproduce observed variability in moisture, there is less agreement between different datasets with regard to tropical ocean precipitation and radiative energy (Fig. 2). There is some indication of enhanced precipitation during warm El Niño years (e.g. 1997/98). However, observed variability appears larger in magnitude than the spread of model simulations (grey shading denotes ±1 standard deviation) and there is substantial discrepancy between the GPCP/SSMI datasets and the Tropical Rainfall Measurement Mission (TRMM) passive microwave (3A11) and active radar (3A26) since 1998 suggesting that improvements are required in data homogenization and inter-calibration.

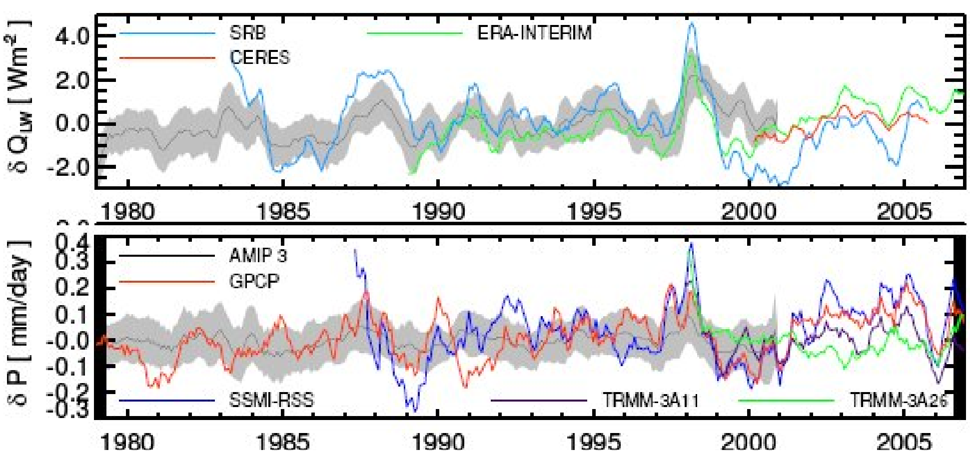
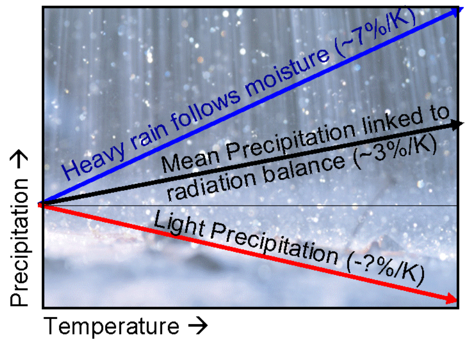


Figure 2**: Time series of deseasonalized tropical ocean atmospheric longwave radiative cooling (Q_{LW}, top) and (bottom) precipitation (P) anomalies for a variety of observations and atmosphere only models (AMIP-3).**

WET AND DRY REGION RESPONSES

Climate model projections have indicated contrasting regional precipitation responses with the tropical rainy-belt and extra-tropical storm-track regions displaying substantial increases in precipitation while arid sub-tropical regions such as the Mediterranean displaying declining precipitation over the 21st century (Meehl et al. 2007). This can be explained in terms of horizontal moisture fluxes (Held and Soden, 2006) but also in terms of the contrasting influence of water vapour and radiative-convective equilibrium on precipitation changes (e.g. Allen and Ingram, 2002). For example, assuming that large-scale precipitation events are determined by moisture convergence, the rise in moisture with warming at the Clausius Clapeyron rate (approximately 7%/K) should dictate a similar rise in precipitation in such regimes (Fig. 3); changes in the moist adiabat and vertical motion within convective events will alter this simple relationship (O'Gorman and Schneider, 2009b; Lenderink and van Meijgaad, 2008).

Global mean precipitation is however determined by radiative-convective equilibrium, with precipitation rising primarily with clear-sky radiative cooling (e.g., Lambert and Webb, 2008) at a rate closer to 3%/K. Depending upon the fractional area of the tropics which is constrained by Clausius Clapeyron (see Fig. 3, right), this will imply a range of responses of dry region precipitation. Thus, the dry region precipitation is expected to increase with warming at a rate lower than mean precipitation, possibly decrease with warming. Fig. 3 demonstrates, using the simple assumptions outlined above and assuming a range of fractional areas of the tropics affected by Clausius Clapeyron that, based on observed wet and dry region precipitation totals, that the threshold in this case is between 10-20% fractional coverage of the tropical Clausius Clapeyron precipitation regime.



$AREA_{WET}$	P_{WET}	P_{DRY}	dP_{DRY}/dTs (mm/day/K)	dP_{DRY}/dTs (%/K)
0.4	6	1	-0.1	-10
0.2	9	1.5	-0.05	-4.5
0.1	10	2	+0.015	+1

***Figure 3*: Schematic representation of trends in global precipitation (left) and (right) idealized estimates in tropical dry region response to surface temperature depending upon the fractional area defined as "wet", using observed estimates to prescribe wet and dry region precipitation (P) and assuming that the wet region precipitation rises at the rate 7%/K.**

Figure 6 attempts to quantify the current wet and dry region responses by conditioning with respect to the zero monthly mean vertical motion contour, using NCEP reanalysis data to sample the satellite data. Sensitivities are calculated for each dataset for the tropical oceans and its wet and dry regions, and also by time-period. Tropical ocean warming is associated with increased precipitation (black) although the magnitude is dependent upon dataset and time-period (John et al. 2009; Liepert and Prevedi, 2009). Nevertheless, there is a clear tendency for wet regions (blue) to become wetter at a faster rate than the mean while dry regions show little response or a reduction in precipitation with tropical ocean warming (e.g. Allan and Soden, 2007).

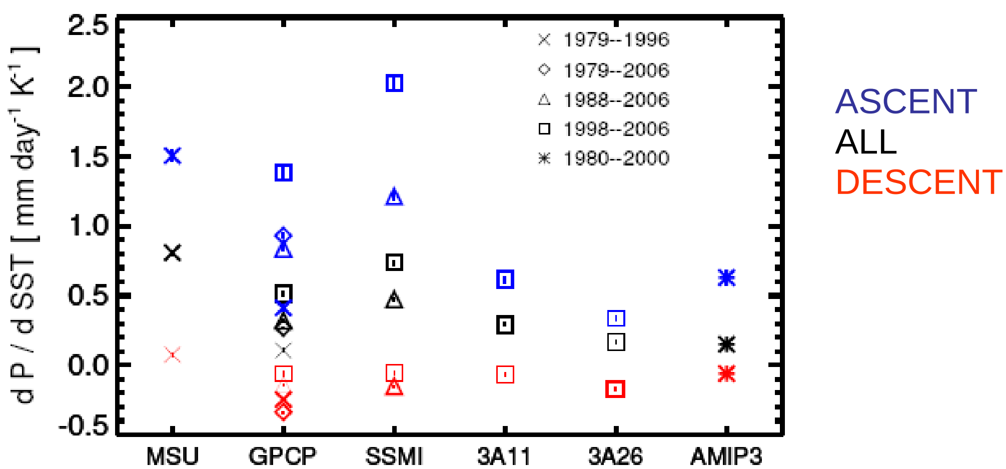


***Figure 4*: Sensitivity of tropical ocean precipitation to sea surface temperature changes for satellite observations and atmosphere-only climate model simulations and conditioned by positive vertical motion at 500 hPa (descent) and negative vertical motion (ascent).**

The use of the zero 500 hPa vertical motion field is rather arbitrary and it is also useful to understand the sensitivity of the precipitation responses to the reanalysis input as well as the vertical motion threshold (w). Figure 7a displays sensitivities for the GPCP ocean data for a range of vertical motion thresholds and using either NCEP or ERA Interim vertical motion fields. The wet region, defined as w<0, displays positive precipitation trends regardless of the reanalysis used to prescribe w. However, trends are smaller for ERA Interim than for NCEP. For the dry regime, trends are more positive using ERA Interim in place of NCEP data although both reanalyses definitions of the dry region display significant drying trends for w>0. It is proposed that spurious trends may be introduced when using the NCEP data since improving accuracy with time will reduce the mis-classification of heavy rain in the dry regime could explain the larger magnitude of trends compared with using ERA Interim to prescribe the wet and dry regions. Therefore the use of dynamical fields from reanalysis for conditionally sampling long-term changes within meteorological regimes may suffer from limitations. One way around this issue is to define wet and dry regions in terms of percentile bins of the precipitation fields themselves (e.g. Allan and Soden, 2008).

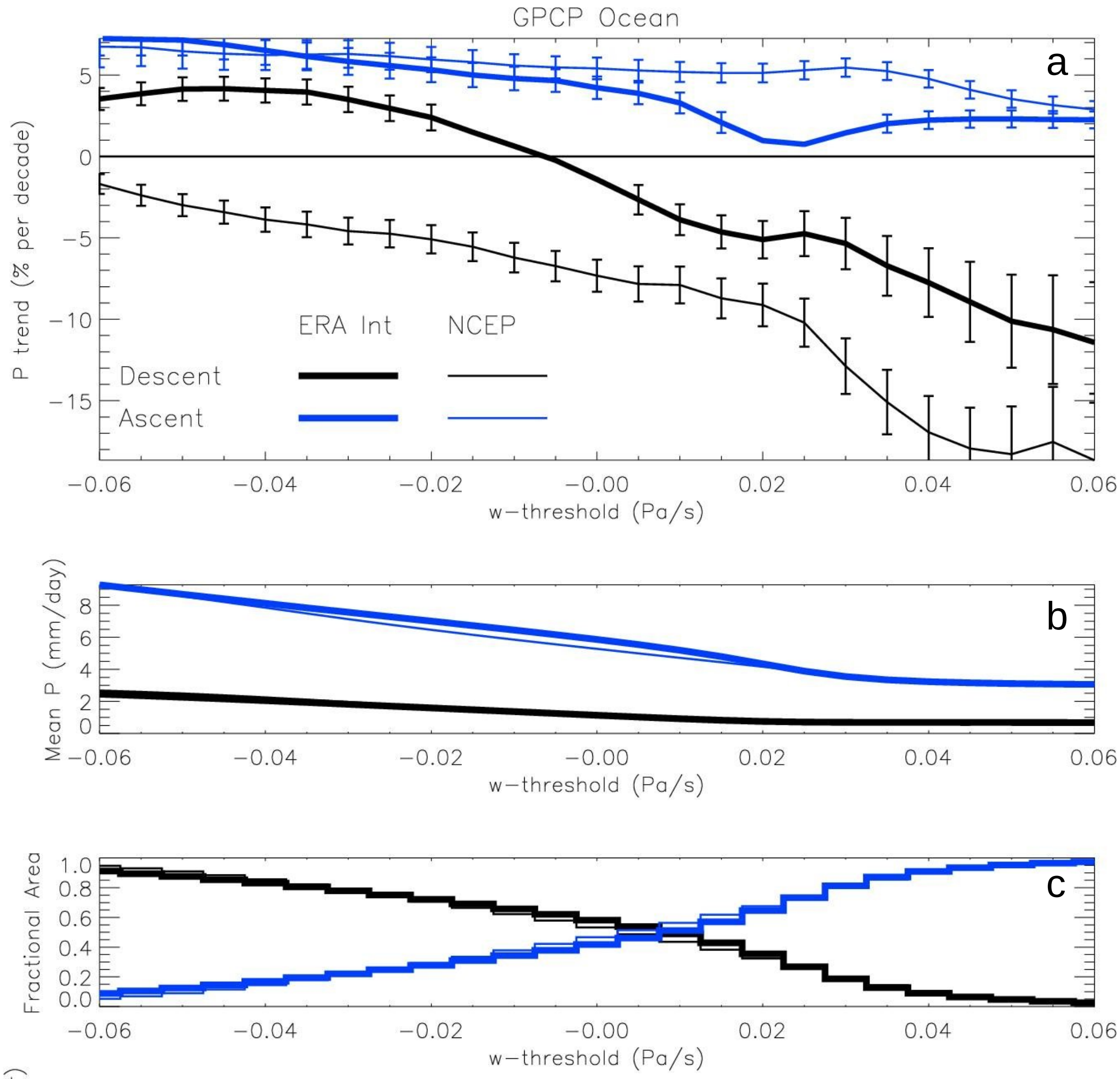


Figure 5: (a) **Precipitation trends, (b) mean precipitation and (c) fractional coverage of wet and dry regions for ranges of vertical motion thresholds and data sources applied to GPCP ocean precipitation.**

EXTREME PRECIPITATION

Changes in extremes of precipitation are now assessed in models and satellite data, following on from comparisons made by Allan and Soden (2008) who found an increased frequency of the heaviest precipitation events with warming, with models appearing to underestimate the response compared to satellite data. Figure 8 shows the precipitation frequency response for individual models and the SSM/I satellite data. While the SSM/I response is 2-3 times larger than the ensemble mean response for the heaviest rainfall regime (99th heaviest rainfall event, excluding dry daily grid boxes), the range in model sensitivities is substantial as noted previously (Gastineau and Soden, 2009; O'Gorman and Schneider, 2009a).

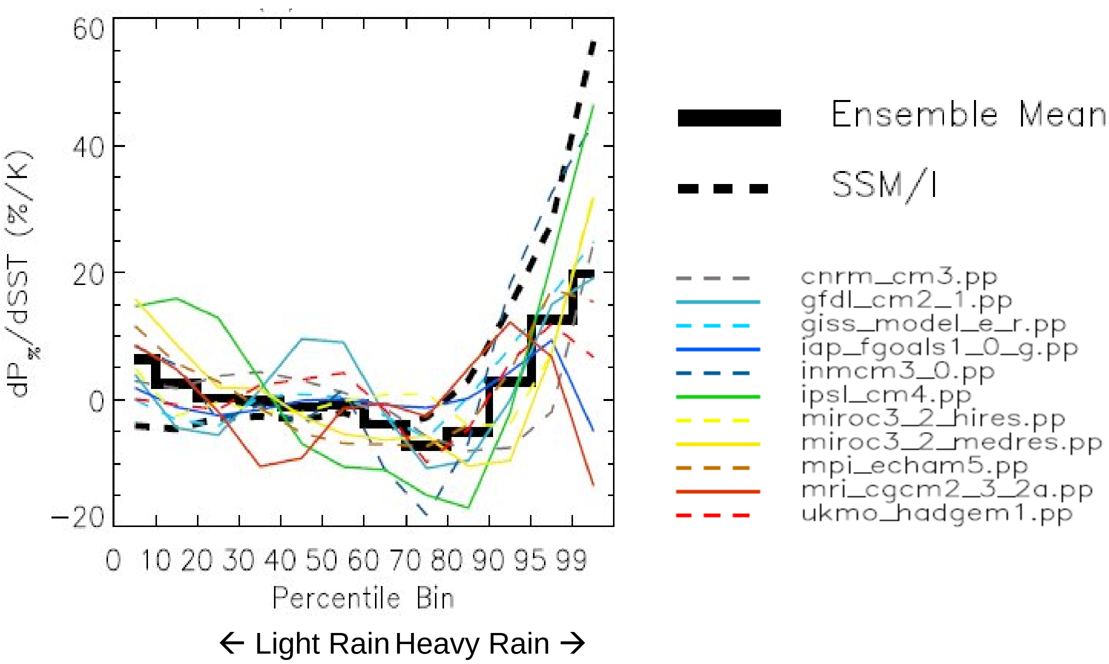


Figure 6: **Changes in the frequency of rainfall in percentile bins of intensity with changes in sea surface temperature for models, the model ensemble mean (1979-2001) and SSM/I daily data (V4, 1987-2004).**

Updates to the above analysis have been developed by Allan et al. (2010) who use an updated version of SSM/I data (v6), a longer period (1987-2008) and compare only the 20% of wettest grid-boxes, including dry grid-boxes in this calculation, thereby ensuring consistent sampling of the wettest regions. Figure 9 displays results for this update, the difference to Allan et al. (2010) being that the entire SSM/I record is treated as an homogenous record. While there are possible dis-continuities in the time series (e.g. 2000-2002), the sensitivity of the SSM/I daily precipitation to warming does not vary substantially, with an increasing frequency of the heaviest rainfall events, rising at around 60% per K warming. Again, the model spread is large for intense precipitation, suggesting considerable uncertainty in future projections of intense rainfall in the tropics (O'Gorman and Schneider, 2009a). For further details, see Allan et al. (2010) and Figure 9.

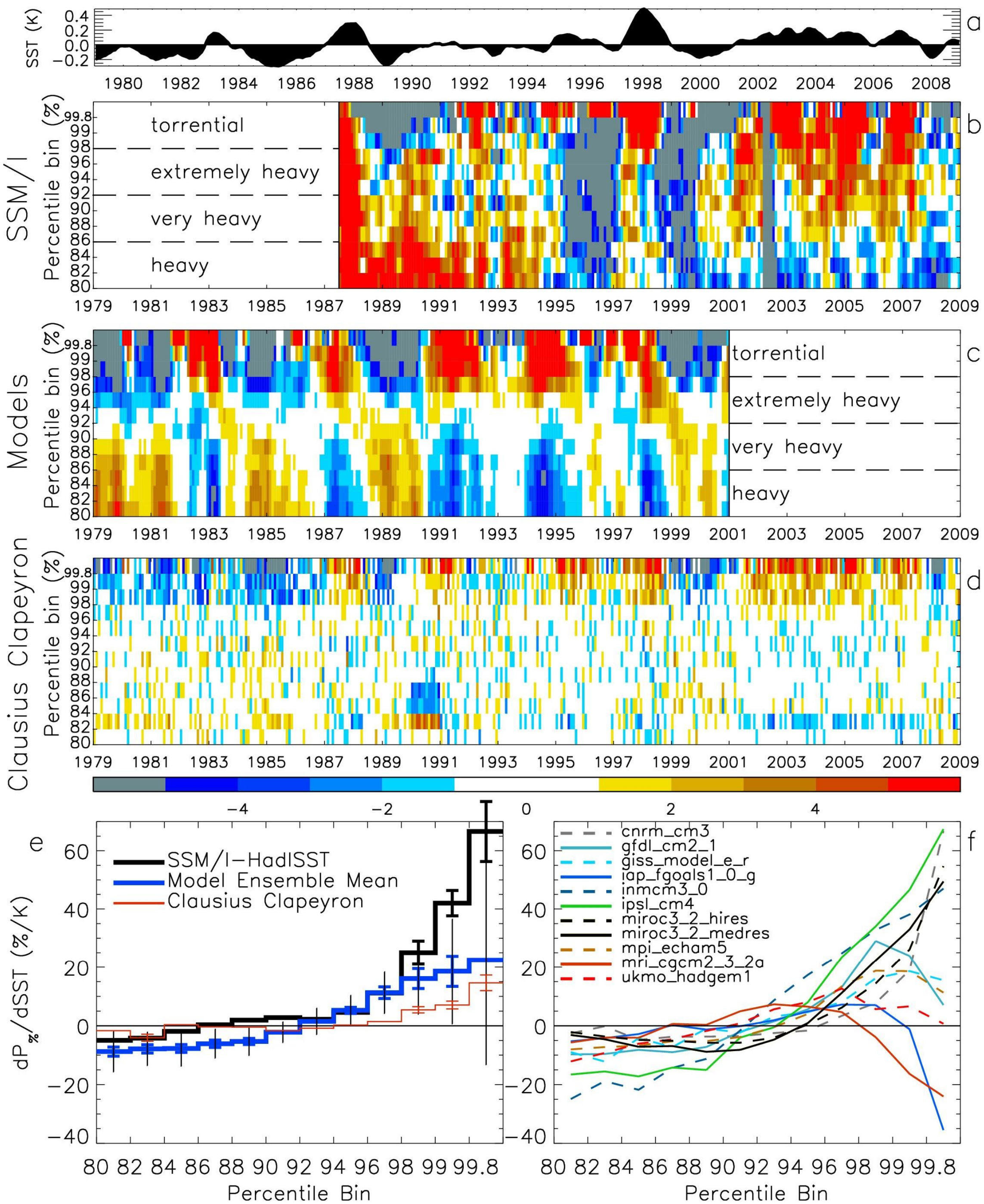


Figure 7: **Percentage changes in the frequency of heavy rainfall events in percentile bins of intensity with changes in sea surface temperature (a) for (b) SSM/I v6, (c) model ensemble mean, (d) SSM/I climatological distribution perturbed by 7% per K warming of local sea surface (Clausius Clapeyron experiment) and the sensitivity of the frequency of rainfall in each bin per K of tropical ocean warming for (e) SSM/I, the Clausius Clapeyron experiment, the model ensemble mean and (f) individual models.**

CONCLUSIONS

Current changes in tropical water vapour, precipitation and its extremes have been described over the period 1979-2008 using observations, reanalyses and atmosphere-only climate model simulations. The following conclusions are:

1) Tropical water vapour rises with temperature in models and observations although reanalyses struggle to capture decadal changes
2) There is strong evidence for enhanced mean and extreme precipitation with warming over an interannual time-scale although large differences exist between models and each of the observational/satellite datasets and the precise relationship is highly dependent upon the time-period
3) There is a tendency for wet regions to become wetter with temperature and with time, at the expense of the dry regions. The magnitude of these trends may be overestimated using reanalaysis vertical motion fields to define the wet and dry regions and may explain larger trends compared to model simulations.
4) Observed increases in the frequency of extreme daily rainfall with warming at around the rate of 60%/K, without relying on reanalysis fields, are captured by some model simulations but model spread is substantial.

Further improvements in the homogeneity and inter-calibration of satellite estimates of precipitation are required before trends in precipitation may be quantified accurately and compared usefully with models. At the same time, the realism of precipitation distributions simulated by models is questionable as are their diverse range of responses to warming. Finally, mean global precipitation is constrained by the radiative-convective balance, so any perturbations to this balance, for example involving aerosol, would imply potential consequences for the hydrological cycle (e.g. Wild et al. 2008, Hegerl and Solomon 2009). Monitoring changes in the Earth's radiation balance in models and observations (e.g. Figure 10) in addition to aspects of the water cycle are therefore crucial in improving our ability to monitor, understand and predict future changes in the Earth's hydrological cycle.

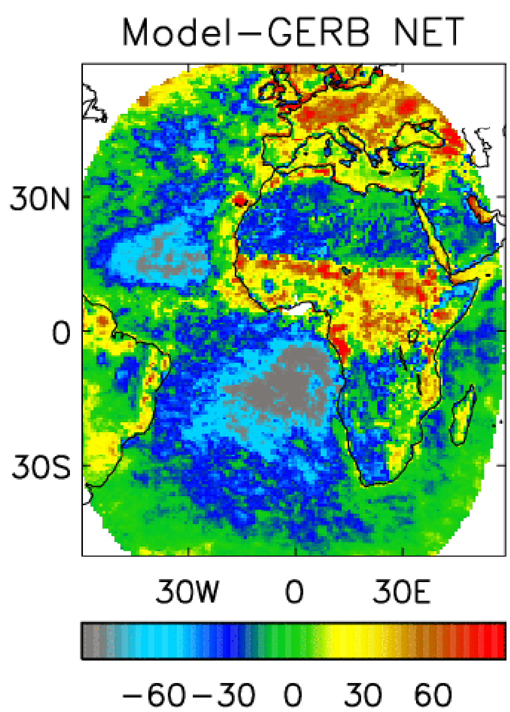


Figure 8: Model minus Geostationary Earth Radiation Budget (GERB; Harries et al. 2005) net top of atmosphere radiative flux difference for 2008. For details, see Allan et al. (2007).

REFERENCES:

Allan, R. P. and B. J. Soden (2007), Large discrepancy between observed and simulated precipitation trends in the ascending and descending branches of the tropical circulation, Geophysical Research Letters, 34, L18705

Allan, R. P. and B. J. Soden (2008), Atmospheric Warming and the Amplification of Precipitation Extremes, Science, 321, (5895) p.1481-1484, doi:10.1126/science.1160787

Allan, R. P., A. Slingo, S.F. Milton and M.A. Brooks (2007), Evaluation of the Met Office global forecast model using Geostationary Earth Radiation Budget (GERB) data, Q. J. Roy. Meteorol. Soc., 133, 1993-2010

Allan, R. P. and co-authors (2010) Current changes in tropical precipitation, Environ. Res. Lett., in preparation.

Allen, M. R., and W. J. Ingram (2002), Constraints on future changes in climate and the hydrologic cycle, Nature, 419, 224– 232.

Harries, J. E. and co-authors, (2005) The Geostationary Earth Radiation Budget (GERB) Experiment, Bull. Amer. Meteorol. Soc., 86, 945-960

Hegerl G. C. and S. Solomon S (2009) The risks of geoengineering, Science, 325, 955-956

John, V.O., R.P. Allan and B.J. Soden (2009), How robust are observed and simulated precipitation responses to tropical ocean warming? Geophysical Research Letters, 36, L14702, doi:10.1029/2009GL038276

Liepert, B. G., and M. Previdi (2009), Do models and observations disagree on the rainfall response to global warming?, J. Clim., 22(11), 3156–3166, doi:10.1175/2008JCLI2472.1.

Lambert, H. F., and M. J. Webb, 2008: Dependency of global mean precipitation on surface temperature. Geophys. Res. Lett., 35, L16706, doi:10.1029/2008GL034838.

Lenderink, G., and E. van Meijgaard (2008), Increase in hourly precipitation extremes beyond expectations from temperature changes, Nat. Geosci.,1, 511 –514, doi:10.1038/ngeo262.

Meehl, G. A., et al. (2007), Global Climate Projections, in Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon et al., pp. 747– 845, Cambridge Univ. Press.

O'Gorman P. A. and Schneider T. (2009a) Proc. Nat. Acad. Sci. 106, 14773-14777.

O'Gorman, P. A. and T. Schneider (2009b) Scaling of precipitation extremes over a wide range of climates simulated with an idealized GCM, J. Climate, 22, 5676-5685

Wild, M., J. Grieser, and C. Schär, 2008: Combined surface solar brightening and increasing greenhouse effect favour recent intensification of the hydrological cycle. Geophys. Res. Lett., 35, L17706, doi:10.1029/2008GL034842.