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March 15, 2010

Dr. Jared Entin
Terrestrial Hydrology Program
NASA Headquarters
300 E Street, SW
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(By email: jared.k.entin@nasa.gov)

Dear Jared

Re: Year 1 progress report (Grant NNX09AK35G)

Attached is our year 1 progress report for grant NNX09AK35G (Development and diagnostic analysis of a multi-decadal global evaporation product for NEWS). As you can see we've made excellent progress over the last year, including providing initial products to Dr. M. Rodell (NASA GSFC) for the NEWS water budget studies.

I appreciate your support of this research.

Sincerely yours

Eric F Wood
Professor

cc: Grants Officier <nssc-ContactCenter@nasa.gov>
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Year 1 Progress Report

DEVELOPMENT AND DIAGNOSTIC ANALYSIS OF A MULTI-DECADAL GLOBAL EVAPORATION PRODUCT FOR NEWS

Grant NNX09AK35G (PI Eric F Wood, Princeton University)

1. Project Overview

Documenting the global water and energy cycle through observations is fundamental to achieve the goals of GEWEX and NASA's Earth Science Research Strategy to obtain a quantitative description of the variations in the global energy and water cycle. Such documentation is needed to enable NASA and its supported NEWS investigators to acquire enhanced knowledge of Earth¿s climate, including characterizing the memories, pathways and feedbacks between key water, energy and biogeochemical cycles. Amongst the various climate cycle variables, surface evapotranspiration (ET) or latent heat flux is often considered the climate linchpin variable because it plays a central role in the water, energy and carbon cycles, and is common to all three. It is unique in providing the link between the energy and water budgets at the land surface; the link between the terrestrial water and carbon cycle through vegetation transpiration, plays a central role in coupling the land and ocean surfaces to the atmosphere, and operates over fast (diurnal) and slow (seasonal) time scales. Much of our understanding of the complex feedback mechanisms between the Earth surface and the surrounding atmosphere is focused on quantifying this process, as well as to determine the biological environment and its water use efficiency. The GEWEX Radiation Panel (GRP), in collaboration with the GEWEX Land Surface Study (GLASS), has launched an activity called LandFlux with the goal of fostering the needed capabilities to produce and diagnose a global, multi-decadal surface turbulent flux data product. The GRP has already supported the development of an ocean surface heat flux activity (SeaFlux). A LndFlux product, coordinated with the SeaFlux product would contribute to the efforts of the NASA NEWS team in their collective effort to further our understanding of the global energy and water cycles.

2. Project Objectives

There is a critical need for the development of multi-decadal, global fields of evaporation for addressing many of the scientific goals and questions of NEWS and the GEWEX LandFlux initiative. Thus the overall objective of the proposed project is:

To provide the NEWS science team, as well as the general climate community, with a multi-decadal, analyzed global scale evaporation product, consisting of a retrieved ISCCP/EOS terrestrial evaporation fields (developed under this proposal) and merged with ocean evaporation fields (from related NEWS investigations); and to carry out diagnostic studies that assess the consistency between the terrestrial evapotranspiration product and other variables of the global water and energy cycle *and the consistency between the ocean and land evaporation products, so to provide error estimates in evaporation.*

This objective will be achieved through the following specific activities and goals:

1. To evaluate the suite of remote sensing data products available from 1983 to present that can be used to produce the land evapotranspiration product.

2. To produce and provide global land fields of terrestrial surface evapotranspiration for merging with NEWS-generated ocean evaporation fields to create global fields of evaporation, and to offer this to the NEWS investigators for their evaluation and use.

3. To carry out diagnostic studies using terrestrial and atmospheric water budget computations to evaluate the consistency of the land and ocean evaporation fields at continental and global scales, and to estimate the magnitude of the error terms seasonally and annually; to carry out similar studies for the land component over continental river basins; and to inter-compare the land evapotranspiration products for the ISCCP and EOS overlap periods to assess the error due to spatial scale between the data sets.

3. Year 1 Progress

Our progress in year 1 has focused on generating initial versions of long-term land ET products, including analyses of the input datasets. Two initial products have been developed base on a remote-sensing orientated Penman-Monteith algorithm for (i) the globe and (ii) a high-resolution version for a case study over Mexico. The former is for land and ocean, although the focus of this project is to produce a land product. The latter demonstrates the potential for downscaling coarse resolution, but long-term remote sensing radiation products to more useful scales. These products are being disseminated to colleagues under the NEWS and LandFlux umbrellas. We next describe the details of these products and their initial evaluations.

1. Generation of initial long-term land ET product

We have generated an initial version of a long-term land ET product based on ISCCP radiation and meteorology data. The dataset is for the period and scale of the ISCCP forcings: 1984-2006, 2.5 degree, globally, and at daily resolution. We use the remote-sensing orientated Penman-Monteith (PM) algorithm of Mu et al. (2007) which is based on the PM equation (Monteith, 1964) and is a revised version of the method presented by Cleugh et al. (2007). The PM is considered the most accurate method for estimating PE and hence ET over large vegetated regions, when all necessary input data are available (e.g. Garatuza et al., 1998). The PM given below models the diffusion of energy from plants or soil against stomatal and aerodynamic resistance, given inputs of net radiation, temperature and humidity.

$$ET = \frac{\Delta R_{net} + (\rho c_p VPD / r_a)}{\Delta + \gamma (1 + \frac{r_s}{r_a})} \quad (1)$$

where Δ (Pa K^{-1}) is the slope of the vapor pressure deficit versus air temperature relationship, R_{net} is the net radiation (W m^{-2}), ρ is the density of air (kg m^{-3}), c_p is the specific heat of air (J kg^{-1} K^{-1}), VPD is the vapor pressure deficit (Pa) and γ is the psychometric constant (Pa K^{-1}). r_a and r_s are the aerodynamic and canopy (or surface) resistances (s m^{-1}), respectively. ET (W m^{-2}) is converted into water equivalent units of mm day^{-1} via the latent heat of vaporization and density of water, and these units are used hereafter. Canopy resistance is derived by upscaling stomatal resistance via LAI and the PM invokes additional environmental adjustments to resistance as a function of VPD and minimum temperature. As recognized by Leuning et al. (2008), stomatal resistance is a key parameter, which varies by vegetation type. Different to Mu et al. (2007), who used a constant minimum stomatal resistance for all vegetation types, we have implemented vegetation dependent values as used in the VIC model and developed by Maurer et al. (2002). Evaporation directly from the soil surface is also calculated as a function of relative humidity and VPD. Note that evaporation from canopy intercepted water in not modeled and that the model parameters, such as minimum stomatal resistances are not calibrated. Potential evaporation and reference crop evapotranspiration are also estimated following Shuttleworth (1993):

$$PE = \frac{\Delta R_{net}}{\Delta + \gamma} + \frac{\gamma}{\Delta + \gamma} \frac{6.43(1 + 0.536u)VPD}{\lambda} \quad (2)$$

$$ET_{rc} = \frac{\Delta R_{net}}{\Delta + \gamma^*} + \frac{\gamma}{\Delta + \gamma^*} \frac{900uVPD}{T_a + 275}, \quad \gamma^* = \gamma(1 + 0.33u) \quad (3)$$

where u is the wind speed (m s^{-1}) and λ is the latent heat of vaporization (J kg^{-1}). Eqn 2 represents the potential evaporation from an extensive free water surface and is equivalent to Eqn. 1, but with r_s = 0 s m^{-1} (i.e. no resistance to transpiration) and standard measurement heights for the meteorology. Reference crop evapotranspiration (Eqn. 3) is an idealized estimate that we compare to the pan observations. It is defined as the rate of evapotranspiration from an idealized grass crop of height 0.12m, an albedo of 0.23 and a surface resistance of 69 s m^{-1}. It is often related to pan evaporation with a pan coefficient (ET_{rc}/pan) which varies by the type of pan, surrounding ground cover (e.g. short grass), and mean humidity and windspeed/fetch conditions. The coefficient is generally of the order of 0.4 - 0.85 for

US class "A" pans and up to 1.1 for sunken Colorado-type pans under low wind conditions (Shuttleworth, 1993).

Required inputs for calculating ET, PE and ET_{rc} are net radiation, R_{net}, (surface short- (SW_{down}, SW_{up}) and longwave (LW_{down}, LW_{up})), surface meteorology (humidity (q), air (T_a) and surface temperature (T_s), pressure (P_s) and windspeed (u)) and surface characteristics (vegetation distribution, LAI, emissivity (ε), albedo (α)). Values of emissivity and albedo are only required if upward SW and LW fluxes are not available. The radiation, meteorology, emissivity and albedo were obtained from the ISCCP database at 3-hourly resolution and aggregated to daily. Windspeed is not available as part of the ISCCP database and so was taken from the latest version of the dataset of Sheffield et al. (2006).

Figure 1 shows the annual values of various components of the surface energy budget taken from the ISCCP data. Given adequate moisture, net radiation (Rnet) is the main driver of evaporation at the land surface. Some of the uncertainties in evaporation derive from uncertainty in the Rnet values and the various short- and long-wave components that contribute to it. Figure 2 shows a comparison of the ISCCP data with that from the NASA Langley SRB datasets, which is a similar set of radiation products using similar underlying cloud and radiance measurements, but with different radiative transfer algorithms. Net radiation is significantly different over the Tropics, because mainly of a positive bias in the downward radiation components and negative bias in the upward components, relative to the SRB. The negative bias in the upward shortwave is due mostly to the low albedo values in the ISCCP. These differences are currently being used to help quantify the uncertainty and errors in the global land ET product.

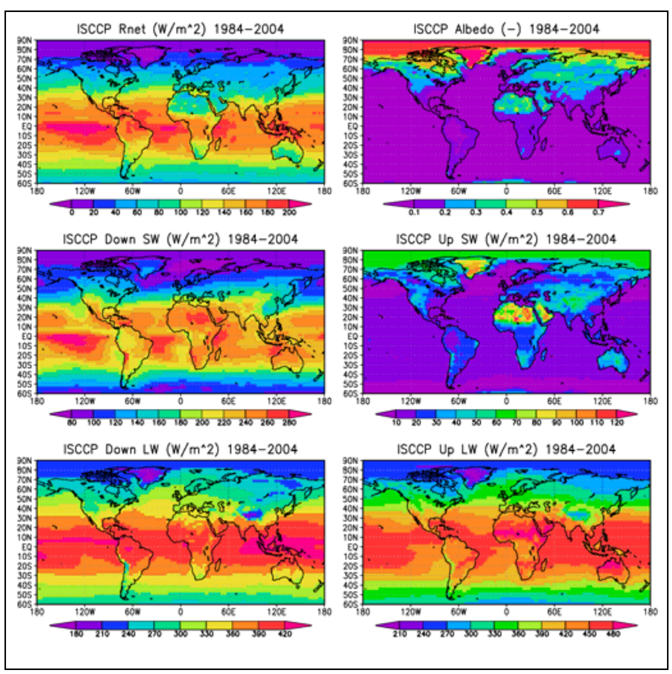

Figure 1. Mean annual surface net radiation and its components from the ISCCP dataset, 1984-2004.

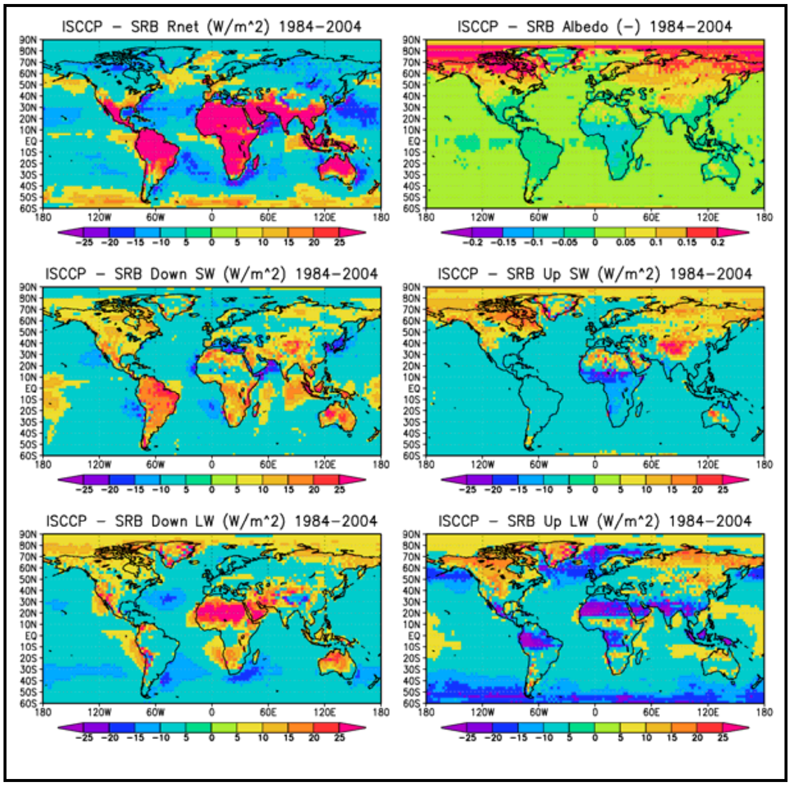

Figure 2. Difference in surface energy components between the ISCCP and SRB datasets. The largest differences in Rnet are over the Tropics. Note the significant differences between the albedo values in central Africa and high latitudes.

The distribution of vegetation cover is taken from the AVHRR-based dataset of Hansen et al. (2000). Values of LAI are specified for each vegetation type that exists in each grid cell by resampling the dataset of Myneni et al. (1997), which is based on AVHRR normalized difference vegetation index (NDVI) values. The LAI values are specified for each month but do not vary from year to year as the AVHRR data do not go beyond mid-2001. Planned updates include the use of the GIMS product which extends to 2006 and will provide year-to-year variation in LAI.

Previously, ground heat flux was estimated as a function of R_{net} that depends on the fractional vegetation coverage, varying linearly between 5 (fully vegetated) and 35% (bare ground) of net radiation (Su, 2002). This has been updated using the algorithm of Tsuang (2005), which uses a Fourier transform of the diffusion of heat equation (e.g. Viterbo and Beljaars, 1995) to model the delayed ground heat flux response to low and high frequency components of surface temperature. The surface temperature is taken from the ISCCP data.

2. Evaluations of the PM-ISCCP Dataset

Initial analysis of the PM-ISCCP dataset indicates that it is reasonable at global scales in terms of the global (land+ocean) long-term water balance that precipitation (P) equals evaporation (E). Average annual P from the GPCP dataset for 1984-2006 is about 2.7 mm/day. The same value from our ET dataset that includes ocean values is about 2.6 mm/day. Given that the initial version of the land ET does not include evaporation from canopy interception (or sublimation from snow), which is estimated to be up to 30% in forested regions, the ET dataset appears to give a reasonable estimate, at least globally.

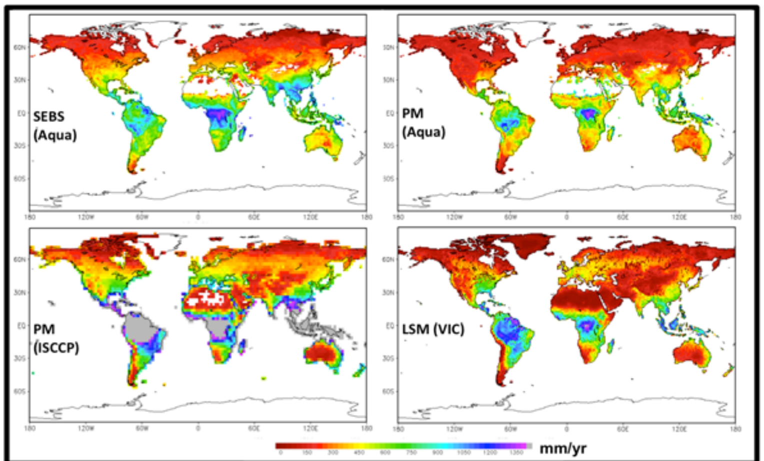

Figure 3. Comparison of four estimates of global annual ET (2003-2006) from the SEBS and PM algorithms based on Aqua data, the PM algorithm using ISCCP data and the VIC land surface model forced by the Sheffield et al., (2006)

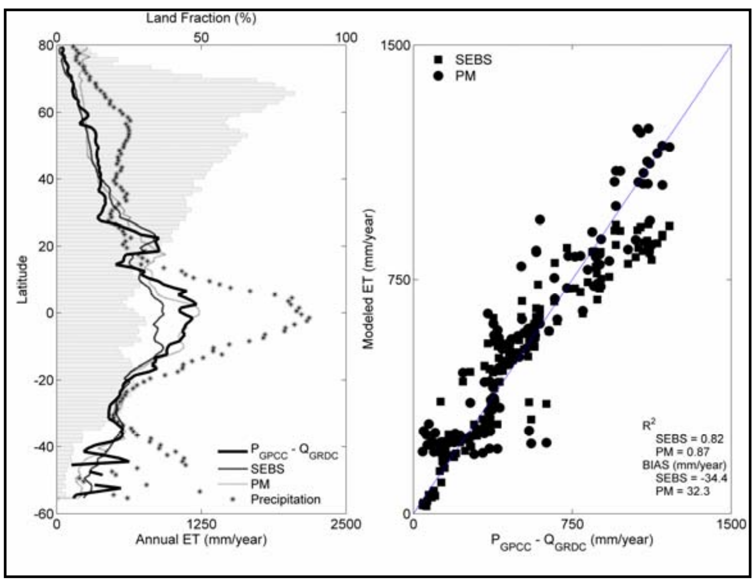

Figure 4. (left) Latitudinal profile (land only) of the ISCCP-PM, Aqua-PM and Aqua-SEBS datasets compared to estimates from observations of P-Q and form the VIC land surface model forced by observational based meteorological data. (right) scatter plot of the same data, where each point represents a 1.0 degree latitudinal band.

Figure 3 shows a comparison of the dataset against similar products produced by the PI over the EOS era using Aqua products at very high resolution (5km) for 2003-2006. The Aqua products are generated using two different retrieval algorithms: the PM algorithm and also the SEBS model, which provides gives an indication of the uncertainty from the model used. They are also compared to ET calculated from the VIC land surface model, which is forced by observational based meteorology and has been calibrated against measured streamflow from a set of large-scale basins across the globe. The VIC dataset additionally simulates sublimation and canopy evaporation, but may underestimate total evapotranspiration because this particular simulation did not include wetlands, lakes and inundation. The spatial patterns are very similar, but the ISCCP-PM may be too high in the Tropics. Figure 4 shows the same datasets as latitudinal profiles for land areas, but additionally compares them to ET as derived from long-term observations of P-Q, and at these scales the ET estimates are reasonably well matched to out best estimates from observations.

3. Development and analysis of long-term, high-resolution regional product for Mexico

We have also applied the ISCCP data to Mexico with the intention of demonstrating the feasibility of downscaling the data to produce high-resolution estimates of ET. We used a downscaling scheme based on the underlying spatial variability of the North American Regional Reanalysis (NARR) and a regional VIC simulation to bring the ISCCP input data to 1/8th degree resolution. Using the downscaled data, ET was calculated using the PM model at daily, 1/8th degree resolution for 1984-2006. The downscaling provides estimates at spatial scales that reflect the heteorogeneity of the land surface (McCabe and Wood, 2008) and which are relevant to water resources planning (Tang et al., 2009). The Mexican region is generally moisture limited but encompasses a wide range of biogeographical, topographic and climatic variation, thus providing a good test of the approach. There also exists a range of long-term datasets of in-situ, reanalysis and modeled data for the region that can be used for evaluation.

Figure 5 shows the ISCCP-PM data (referred to as RS-PM in the figure) compared to that from the VIC simulation. The VIC model was calibrated to observed streamflow for a set of small, unmanaged basins across the country and so likely gives our best estimate of regional ET. The figure shows that their spatial distributions are similar, with a tendency for the ISCCP-PM data to be lower in the summer and autumn that is generally confined to the warmer and more humid coastal regions.

4. Uncertainties and Error Estimates

Uncertainties in the retrievals are derived from the underlying retrieval model (e.g. PM, SEBS), the forcing data (e.g. ISCCP or SRB radiation) and issues of scale in the temporal and spatial domains. Error estimates can also be assessed by comparison with independent measures of ET. We have carried out a number of analyses related to this, mainly for the regional application to Mexico, but are currently progressing towards doing this at larger scales depending on the availability of comparison data (initial results for the global dataset are described above). For Mexico, the forcing data and calculated ET (and potential evaporation, PE) have been evaluated against other large-scale estimates from reanalysis and off-line hydrologic modeling. We also calculated a reference crop evapotranspiration and compared these to local estimates from a large database of evaporation pans. We have used these evaluations and the uncertainties in the input data to estimate the uncertainty in the derived ET as shown below and described in Sheffield et al. (2010).

We have carried out some comparisons of the impact of the forcing data on the retrievals, in particular the impact of uncertainty in radiation forcings and vegetation characteristics. Related work (Ferguson et al., 2009) has indicated that differences in vegetation datasets (including LAI) have a much larger impact on the

ET estimates, than, say uncertainty in the inter-annual variability in LAI. To assess the impact of uncertainties in vegetation we therefore also used land cover and LAI data developed for the North America Carbon Program (NACP) as derived from NASA's MODIS. The NACP LAI data have been gap-filled and smoothed by Gao et al. (2008) to allow for cloud contamination and other factors, which affect the quality of the retrievals. These data were sampled from their native 1km resolution to 1/8th degree in a similar manner to the AVHRR data.

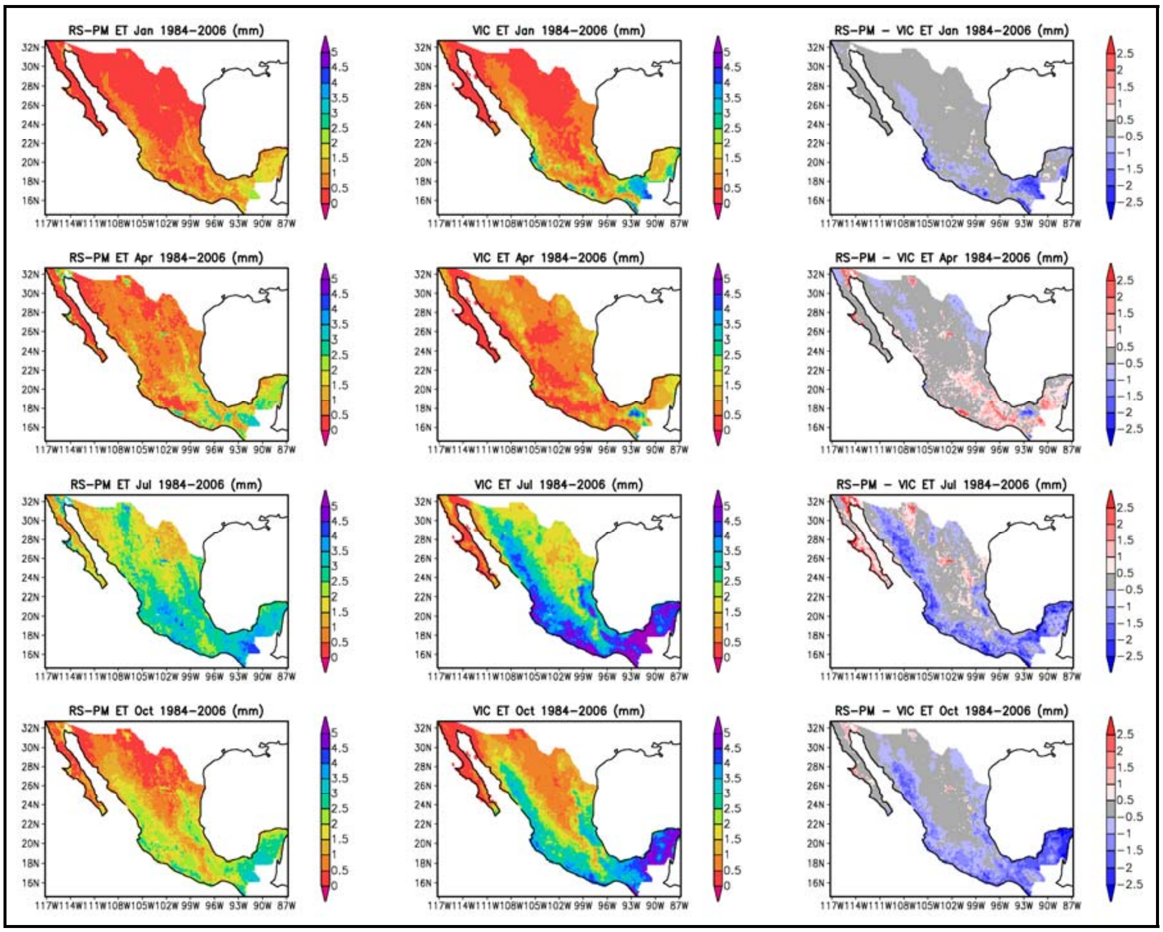

Figure 5. Mean seasonal maps of ET from ISCCP-PM, VIC and their difference (ISCCP-PM – VIC) for 1984-2003.

Figure 6 shows an estimate of the uncertainty in the PM based on the uncertainties in the input Rnet and vegetation data and compares this with the uncertainty in our best estimate of large scale ET from NARR and VIC. Overall, the PM and NARR-VIC estimates overlap in all months but less so in the spring and autumn, when the PM is biased high and low respectively. The uncertainty in the PM values range from 0.19 to 0.49 mm day-1. The NARR-VIC values from 0.31 to 1.24 mm day-1.

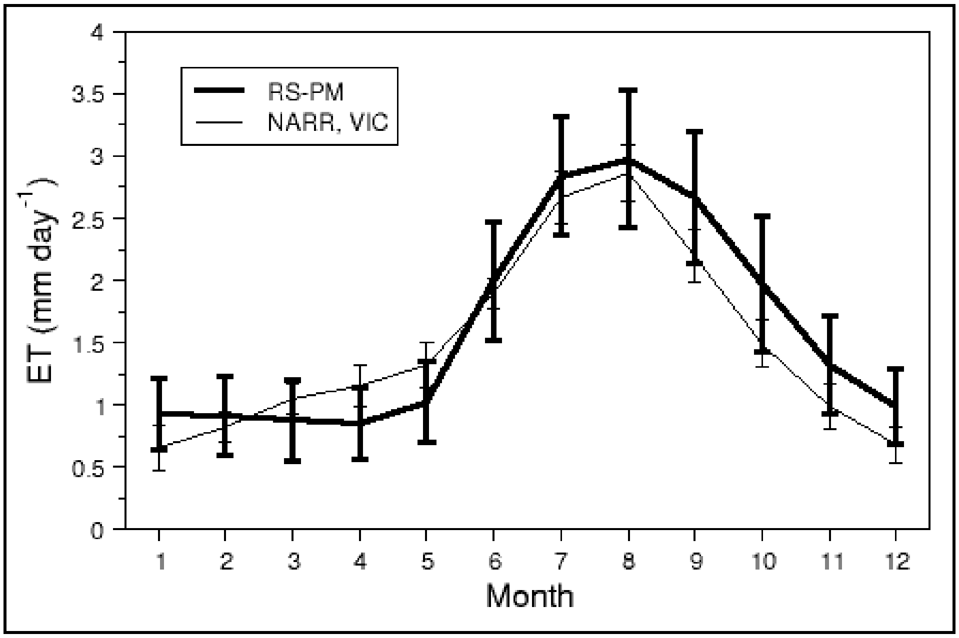

Figure 6. The uncertainty in the ISCCP-PM estimates of ET (mm day^{-1}) compared to the uncertainty in our best estimate of ET as derived from the NARR and VIC. The lines are the mean of the ensemble of ISCCP-PM estimates (thick line) and the mean of the NARR and VIC (thin line). The error bars represent 95% confidence limits on the estimates as derived from the standard deviation of the spread in the estimates.

5. Delivery of products to NEWS and Landflux

An essential part of the project is to interact with other NEWS investigators to compare and merge products. To this end we have worked with the PI Matt Rodell and the NEWS team to provide the initial versions of the global ISCCP-PM and SRB-PM datasets. The data have also been provided to the LandFlux evaluation group led by collaborators at ETH Zurich and Observatoire de Paris, France for an inter-comparison with other remote sensing and empirical estimates, reanalysis, GCMs and off-line land surface models.

6. Publications and conference/workshop presentations

The data have been presented as part of the Landflux program at the following workshops and symposiums:

- GEWEX-WATCH International Symposium on Global Land-surface Evaporation and Climate, Wallingford, 2009.
- GEWEX-iLEAPS LandFlux Workshop, Melbourne, 2009.

Other presentations:

- Sheffield, J., and E. F. Wood, (2009), Development of a long-term evapotranspiration product for Mexico from remote sensing, International

Conference on Land Surface Radiation and Energy Budgets: Observations, Modeling and Analysis, Beijing, March 18-20, 2009.

- Vinukollu, R K, Sheffield, J, Ferguson, C R, Pan, M, Wood, E F (2009), Developing Evapotranspiration Data Records for the Global Terrestrial Water Cycle, Eos Trans. AGU, 90(52), Fall Meet. Suppl.

The Mexican high-resolution data have been published as:

- Sheffield, J., E. F. Wood, and F. Munoz-Arriola, 2010: Long-term regional estimates of evapotranspiration for Mexico based on downscaled ISCCP data. J. Hydrometeor., in press.

Future Plans

In year 2 of the project we intend to focus on refining the ISCCP-PM and EOS-based datasets through analysis within the water and energy budget framework. As well as the comparisons shown above, we will extend the analysis to evaluations at CEOP sites, and across a multitude of small basins globally that provide long-term estimates of precipitation and streamflow, which can constrain our estimates of ET. Furthermore, we will develop alternative estimates using the two other retrieval algorithms (SEBS and Priestley-Taylor), which will help quantify model-derived uncertainty. Development of techniques for downscaling the data to at least 0.5 degree resolution, globally, will be explored, with an initial direction based on our experience with the high resolution retrievals for Mexico based on reanalysis data. At global scales this can be done using one of the global reanalysis datasets, in particular the NASA MEERA reanalysis which is available at 0.5 degree resolution for 1979-present, supplemented with information from our EOS-era ET estimates that are available at sub-5km resolution.