Characterization of turbulent latent and sensible heat flux exchange between the atmosphere and ocean in MERRA

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Research Objectives

The recently produced Modern Era Retrospective-Analysis for Research and Applications (MERRA; Rienecker et al. 2011) provides a high-resolution dataset that can be used to examine components of the Earth's surface energy and water balance. Latent and sensible heat exchanges between the ocean and atmosphere are fundamental components of these balances and are the focus of this study. The primary objectives are to characterize the MERRA surface energy fluxes with respect to their:

1. **Accuracy against direct measurements;**
2. **Large scale spatio-temporal variability and representation of extremes;**
3. **Connection to forcing by the data assimilation system.**

Summary Points

1. MERRA produces estimates of the turbulent fluxes that agree very well with observational estimates for average conditions; however, it is distinct in amplitude with a particularly weak representation of the surface heat fluxes over the western boundary currents and in conditions of very weak and very strong near-surface stratification. A weaker covariability between wind speed and temperature/moisture stratification than observed exists.

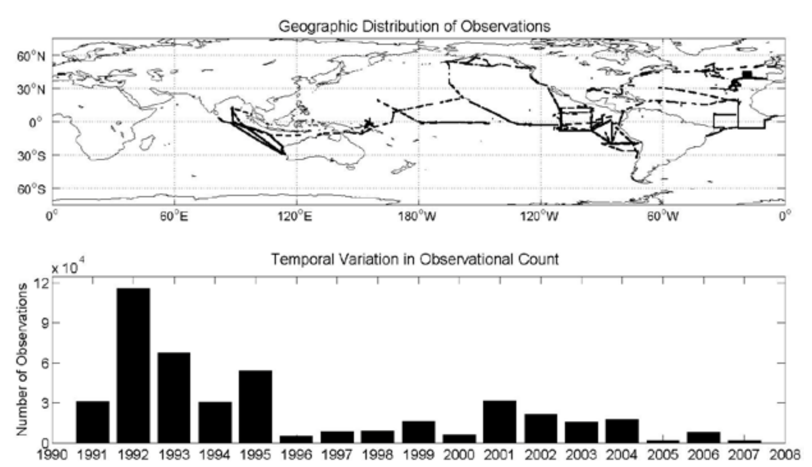
1. MERRA has slightly weaker seasonal variability of the latent and sensible heat fluxes compared to an observational ensemble estimate. It tends to under-represents the occurrence of strong, episodic events compared with observations in the Northern Hemisphere mid-latitudes.

1. Data assimilation, as expected, tends to drive the analysis closer to the observational ensemble; the impact on near-surface variables contains a systematic response to the changing observing system and could introduce artificial trends into the analysis.

Observational Database

High-quality, direct *in situ* measurements of the turbulent latent and sensible heat fluxes and near-surface variables serve as a standard against which the veracity of turbulent flux products are compared. The SEAFLUX (Curry et al. 2004) program has compiled a large dataset of these measurements and are utilized in this study for validation purposes. The spatial and temporal distribution of these observations are characterized below (Fig. 1).

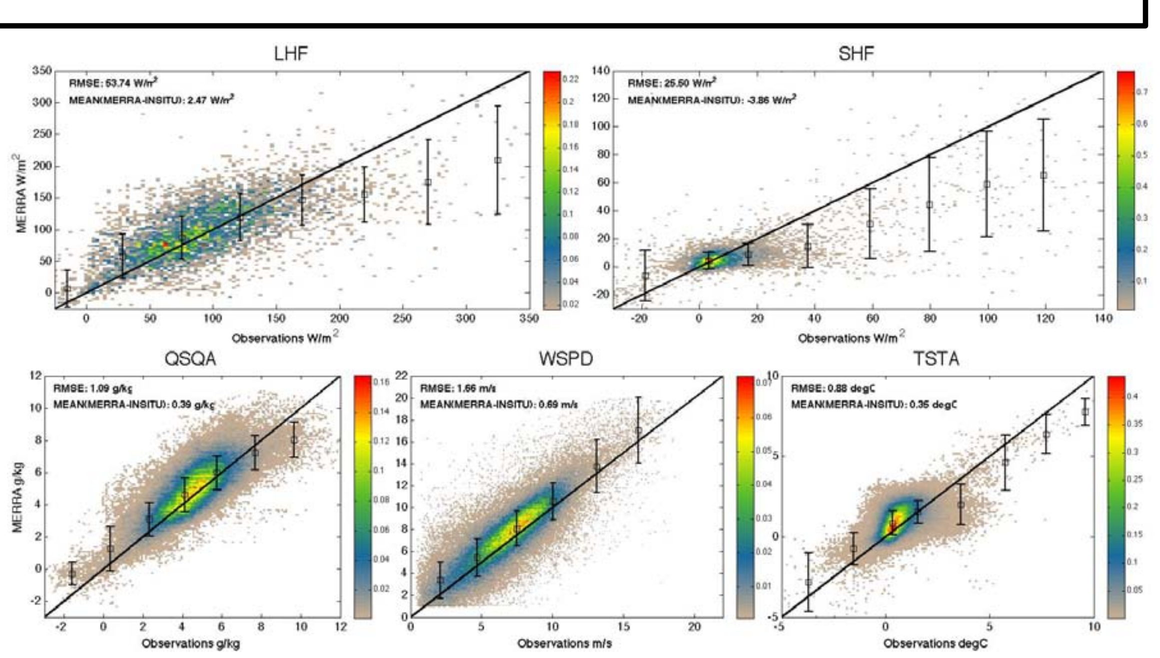
Figure 1.



Comparisons to Direct Measurements

Joint density estimates (Fig 2.) of the surface latent heat flux (LHF), sensible heat flux (SHF), near-surface vertical gradients of moisture (QSQA), wind speed (WSPD), and temperature (TSTA), present the relationship between estimated (MERRA) and observed variables important to surface energy flux calculations. Shading provides an estimate of the population density (normalized to unity) while binned scatterplots provide estimates of the bias and r.m.s. error as a function of the observed variables. The fluxes exhibit small bias and r.m.s error over the most densely populated region. However, MERRA struggles to reproduce strong near-surface gradients leading to stability-dependent biases. Wind speeds tends to be overestimated in MERRA in comparison to observations over all ranges.

Figure 2.



Evaluating Large Scale Variability

Validating surface heat flux estimates at large spatial and temporal scales relies on intercomparisons between multiple estimates and the use of physically based constraints. Further support is provided through the use of local or regional comparisons to direct observations. This study makes use of three additional products to characterize the large scale variability of the MERRA surface turbulent fluxes. These products and their primary data sources are:

1. **OAFlux 3.0 (Yu et al. 2008) / Satellite, Buoy, VOS, Reanalyses**
2. **GSSTF2b (Shie et al. 2009) / Satellite**
3. **NOCS 2.0 (Berry and Kent, 2009) / VOS**

The ensemble mean of these products is used to characterize the annual mean (Fig. 3, right) estimate from MERRA. The differences between MERRA and observationally-based estimates show that MERRA captures the major patterns; however MERRA tends to underestimate the latent and sensible heat flux over the western boundary currents by 50Wm^{-2} and 15Wm^{-2}, respectively. There are outside the range (hatching) of any of the available observationally-based estimates. Within the tropics, MERRA LHF and SHF are less than 10Wm^{-2} from the ensemble estimates. For an annual mean, WSPD estimates from MERRA are larger, the QSQA is too large in the tropics, and TSTA appears too large poleward of 15°.

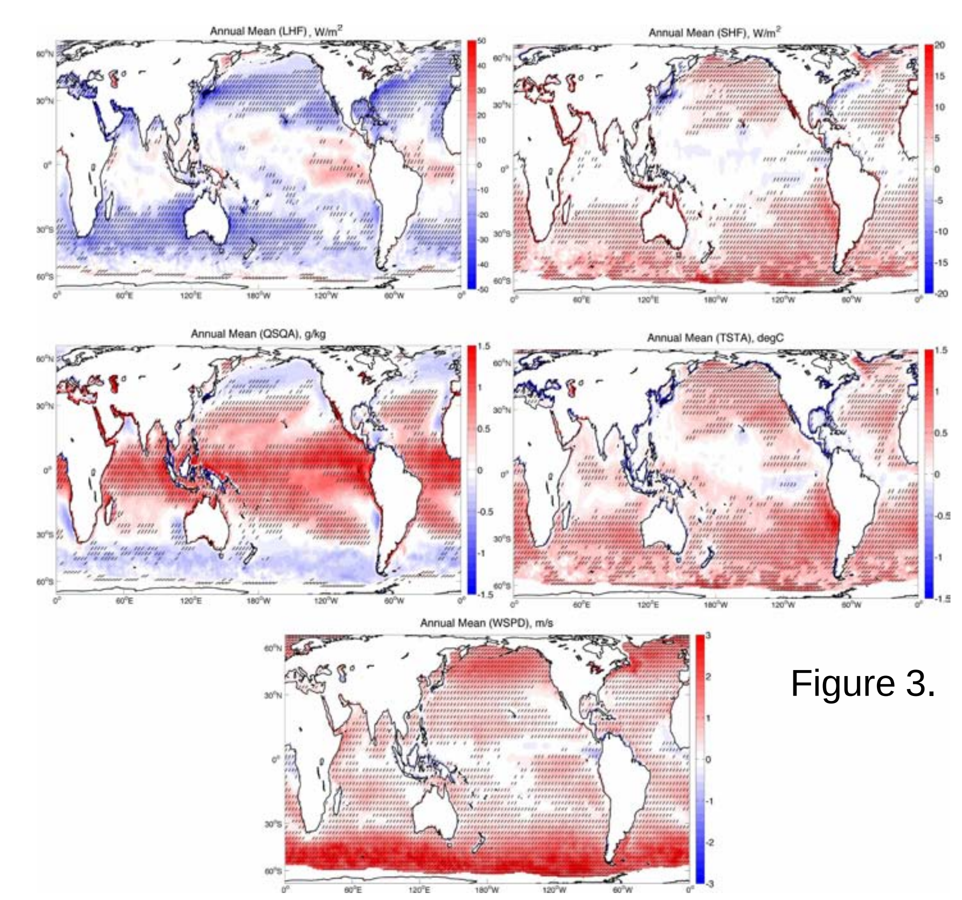


Figure 3.

Seasonal Covariability

The results of Fig. 3 appear inconsistent given the nature of the bulk heat flux relationship. It may be expected that the annual mean LHF should be overestimated in the tropics and western boundary currents given too large (annual mean) near surface gradients of humidity and wind speed. Decomposing the bulk flux relationships into annual mean (uppercase) and anomalous (lowercase, primed) components is accomplished using:

$$LHF=\rho C_e L_v(\Delta Q+\Delta q')(U+u')$$

where ρ is the density of air, C_e is the humidity exchange coefficient, and L_v is the latent heat of vaporization.

The average of the boreal winter season of the distributed terms are depicted in Fig. 4. Indeed, the annual mean flux of MERRA (left panel) is overestimated in comparison to the observational ensemble pattern (right panel). The patterns involving either u' or q' are driven by the seasonal cycle. MERRA tends to have a larger WSPD seasonal cycle and smaller QSQA cycle. MERRA contains weaker covariability between WSPD and QSQA than the observational ensemble.

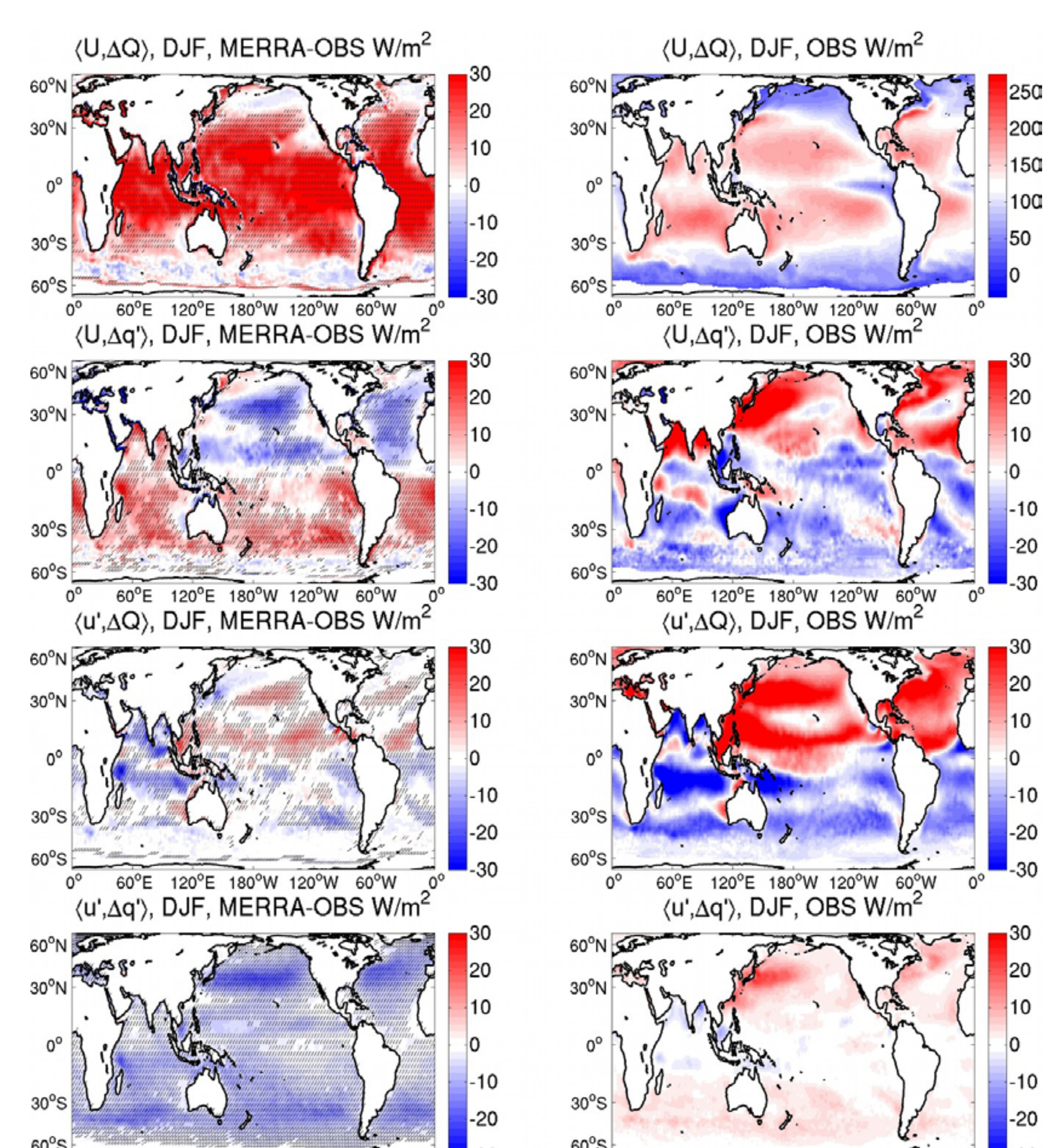


Figure 4.

Representation of Extremes

Climatological-mean values of different datasets provide important information on one component of the distribution. Infrequent, yet strong episodic events are another important component of the surface heat flux distribution and are captured in the extremes of the distribution.

Zonal means of the 5th and 95th percentiles plots (Fig. 5, right) present a representation of the distribution of the surface energy fluxes and near-surface variables in MERRA (thick) and the observational ensemble (OE ; thin + range). The 95th of MERRA LHF are within the range of the OE except in the latitude range 25°-35°N, a region containing the western boundary currents. The SHF estimate is fairly consistent with the OE at all latitudes for both the 5th and 95th percentiles. While QSQA and TSTA are in the OE range over the midlatitudes, the WSPD is too strong. However, too small LHF implies a weaker covariability between extremes in WSPD and the near-surface temperature and moisture gradients.

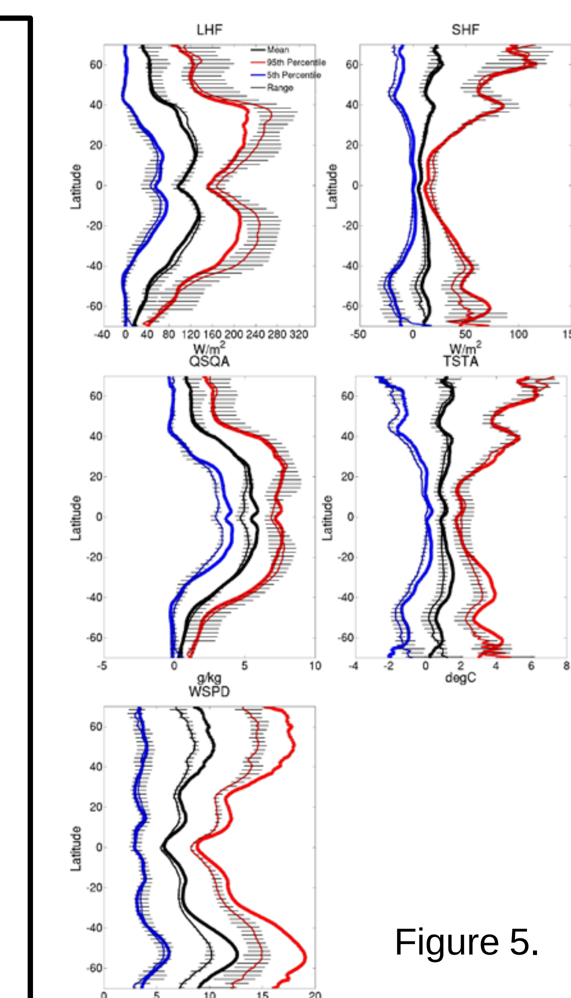


Figure 5.

Impact of Data Assimilation

MERRA is a unique analysis in that the analysis increment – the forcing tendency driven by the assimilation system – are readily available to help interpret the impact of data assimilation (DA). The DA drives tendencies in (among others) moisture, temperature, and momentum (Fig 6., left panel). The annual mean forcing tends to moisten the near-surface layers, adding roughly 5%-10% of the daily average moisture per day in many regions. The temperature increments generally covary with moisture (i.e. moisten and warm, dry and cool) except over cloud-topped boundary layers to the west of South America and Africa. As expected, these adjustments tend to bring MERRA closer to the observational ensemble.

Evaluation of changes in the increment before and after 1998 (right panel) indicate that the inclusion of new satellite sensors, such as AMSU-A, increased the near-surface moisture increment in the Southern Ocean and tended to reduce the required surface air temperature warming and wind speed reduction.

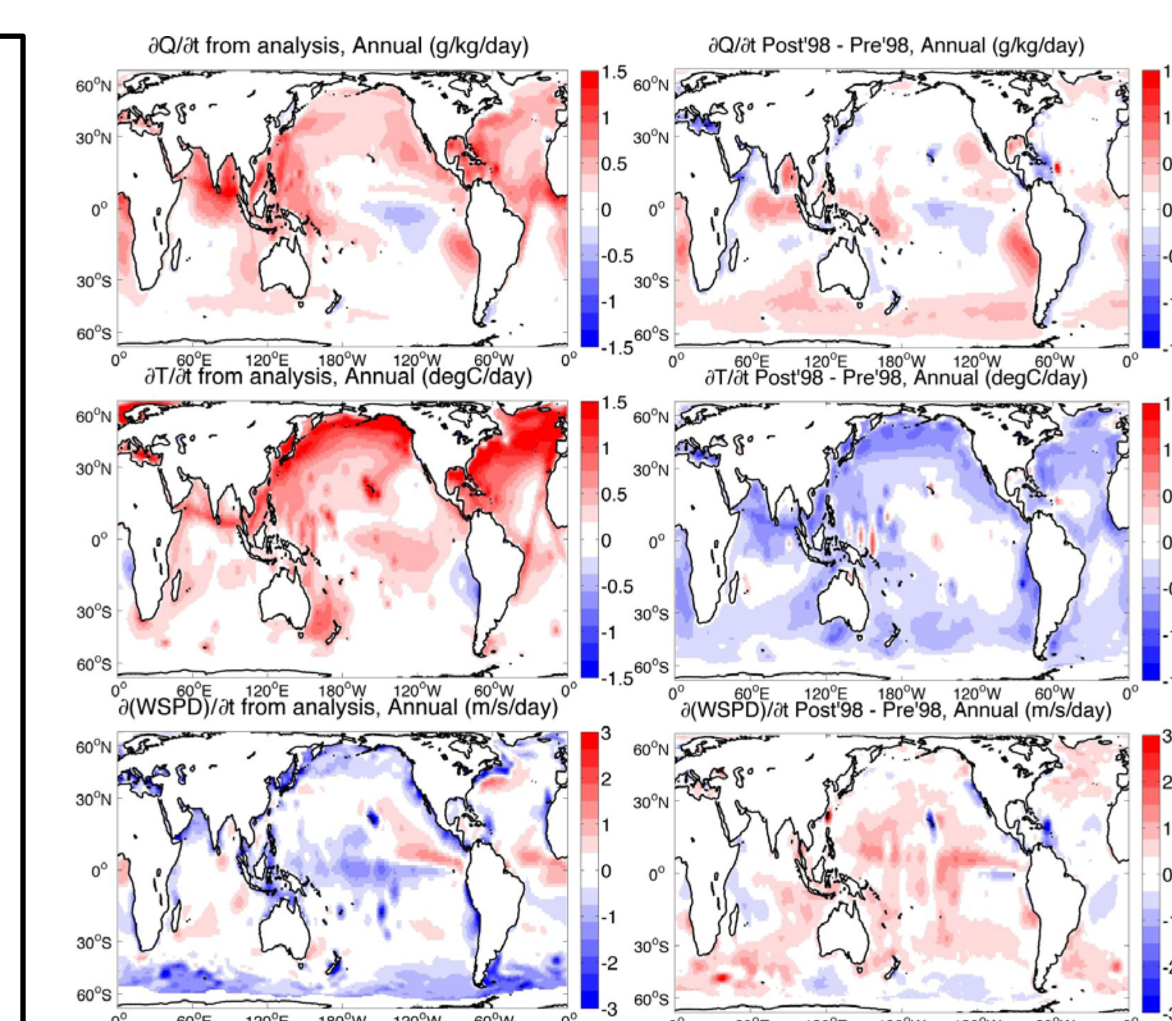


Figure 6.