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:

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

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 and wind speeds tend to be overestimated in MERRA in comparison to the observational ensemble. Wind speeds are characterized below (Fig. 1).

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 accuracy of turbulent flux products are compared. The SEAFLUX (Cury 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).

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 these 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, VOS
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 observational 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 10Wm⁻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 pattern (right panel). The patterns contain weaker covariability between WSPD and QSQA than the observational ensemble.

Seasonal Covariability
The results of Fig. 3 appear inconsistent given the nature of the bulk flux relationships. It is expected that the annual mean LHF should be overestimated in the tropics and underestimated in the extratropics; however, this annual mean flux relationships into annual mean (supercooled) and anomalous (snow-free, primed) components is accomplished using:

\[ \text{LHF}_{\text{primed}} = \frac{p}{C_v} \left[ q_{\text{primed}} (U + u') \right] \]

where \( p \) is the pressure in the density of air, \( C_v \) is the humidity exchange coefficient, and \( L \) 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. The patterns involving either \( u' \) or \( q' \) are driven by the seasonal cycle. MERRA tends to have a larger WSPD seasonal cycle and QSQA cycle. MERRA contains weaker covariability between WSPD and QSQA than the observational ensemble.

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 temperature increments generally covary with weaker forcing tendencies in the tropics, adding roughly 5%-10% of the daily average temperature change. The moisture increments generally covary with stronger forcing tendencies in the tropics, adding roughly 5%-10% of the daily average moisture per day in many regions. The temperature increments generally covary with weaker forcing tendencies 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.

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.
2. MERRA has slightly weaker seasonal variability of the latent and sensible heat fluxes compared to an observational ensemble estimate. It tends to under-represent the occurrence of strong, episodic events compared with observations in the Northern Hemisphere mid-latitudes.
3. 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.

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 (left) and the observational ensemble (OE, thin + range). The SHF 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.

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