ESTIMATION OF SURFACE LATENT HEAT FLUX FROM TRMM

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Abstract

The Visible Infrared Scanner (VIRS) and the Tropical Rainfall Measuring Mission (TRMM) microwave imager (TMI) are used to retrieve sea surface temperature, near-surface air specific humidity, and wind speed. All three variables are used within a bulk parameterisation scheme to compute latent heat fluxes employing some additional empirical assumptions. Results of comparisons to buoy measurements led to several adjustments of the retrieval schemes. The most important two corrections concerned the description of the water vapour absorption continuum in the infrared radiation transport model and the TMI calibration. The application to data during April 1998 showed that the sampling is sufficient to compute monthly averages. The comparison to the Hamburg Ocean and Atmosphere Parameters and Fluxes from Satellite Data (HOAPS) and one month of ECMWF analysis data showed substantially differences between all three data sets.

1. Introduction

The working group on air-sea fluxes jointly established by the World Climate Research Program's Joint Scientific Committee and the Scientific Committee on Oceanic Research has identified four classes of requirements for ocean atmosphere heat flux estimates defined by different types of studies. These are flux fields on high time and space resolution, typically 3 hours and 50 km, needed for example for forcing ocean general circulation models or for regional weather nowcasting and prediction. The second class is for flux fields on longer space and time scales but with high absolute accuracy probably useful for the evaluation of climate models. A third class is defined by climate variability studies where again a high absolute accuracy is desirable but consistency and continuity over long time periods is the primary need. The final requirement is for high quality verification data needed by Numerical Weather Prediction (NWP) models to verify the model physics through the use of independent estimates of the basic meteorological variables and the surface fluxes.

Satellite data have the potential to be useful for all of this classes. Future satellite systems will deliver higher space/time resolutions so that those data are applicable for the first class. Recently, global satellite-derived flux fields have become available (Chou et al., 1997; Grassl et al, 2000) and the length of the time period is significantly increasing. But great care is needed to provide flux estimates from sensors on successive satellites or from combinations of similar sensors on different satellites so that the final product may be useful for the detection of long-term trends in the surface fluxes. At the moment the length of the time record of satellite-derived fluxes allows only for analysing annual and interannual variability which might be useful for validating climate models. In this context any improvement of the flux estimates itself through improved sensors or sensor combinations, e.g. the inclusion of TRMM in the SSM/I network to reduce sampling errors, is meaningful.

One of the problems of older estimates of latent heat fluxes from satellite data is that the instruments needed to derive the variables for the parameterisation were flown on different satellites, e.g. the Advanced Very High Resolution Radiometer (AVHRR) for sea surface temperature on the NOAA series and the Special Sensor Microwave/Imager (SSM/I) for winds and atmospheric humidity on the DMSP series which results in the use of weekly averages of sea surface temperature together with instantaneous estimates of winds and air humidity from SSM/I measurements (Schulz et al., 1997). Aboard the Tropical Rainfall Measuring Mission (TRMM) satellite for the first time both passive infrared and passive microwave instruments are combined on one satellite facilitating a more consistent estimate of surface latent heat flux. The additional 10 GHz channels of the TMI are expected to lead to an improved wind speed retrieval in tropical regions compared to SSM/I retrievals.

This paper describes the adaptation of retrievals used with AVHRR and SSM/I to the TRMM instruments Visible Infrared Scanner (VIRS) and TRMM Microwave Imager (TMI) as well as the validation versus buoy measurements and then shows comparisons to an older estimate from AVHRR and SSM/I measurements and to results from the ECMWF analysis. In section 2 the different data sources employed for this study are described. Section 3 gives a short overview about the parameterisations, retrieval schemes, and empirical assumptions involved in the estimate of latent heat flux at the surface. It also briefly discusses the validation results for the retrievals of basic state variables as sea surface temperature, air specific humidity, and wind speed. Section 4 shows comparisons to ECMWF analysis and the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data (HOAPS) data set.

2. Data

For the whole project five different types of data have been employed:

- TRMM satellite data for the period January 1998 - August 1998 including measurements from the TMI and the VIRS.
- Radiosonde data entering the radiative transfer calculations for the theoretical development of the retrieval schemes. These are from different scientific experiments covering the tropical ocean and represent the oceanic and atmospheric variability.
- Measurements from moored buoys operated by the U.S. National Buoy Data Center (NDBC) for the validation of the satellite-retrieved variables. Unfortunately most of the buoys are located at the coastline of the United States and no buoy on the southern hemisphere was available.
- HOAPS data for April 1998 for a comparison of the new TRMM product to the classical satellite methods for deriving latent heat flux. HOAPS is a climatology derived from AVHRR and SSM/I data and provides pentad and monthly averages over the whole SSMI/ record.
- ECMWF analysis data for April 1998 to make first steps of using satellite-derived basic state variables and latent heat flux to evaluate ECMWF products. The ECMWF data were available on regular 0.5° 0.5° grids with a time resolution of 6 hours.

3. Parameterisation and retrieval algorithms

The latent heat flux is parameterised using the bulk approach given by:

$$Q_L = \rho L_E C_E U(q_s - q_a) \tag{1}$$

where ρ is the air density, U is the wind speed, L_E is the latent heat of evaporation, C_E is the Dalton number or the transfer coefficient, q_s is the saturation specific humidity at the surface computed from the sea surface temperature T_S, and q_a is the air specific humidity at a hight of 20 m. Major components of eq. (1) like U, T_S, and q_a are derivable from VIRS and TMI data. All other variables have to be chosen empirically or inserted from other sources like re-analyses, in situ data, or alternative satellite data. The use of re-analyses data might be superior to empirical assumptions but prevents a model independent determination of the energy fluxes. Schulz et al. (1997) discussed the errors that were introduced using a constant pressure and different assumptions for the not measurable surface air temperature within the bulk approach. Errors in surface pressure compensate each other through their contrary effect on q_S and ρ. In the present version a constant relative humidity of 80% have been assumed to compute the surface air temperature T_a from the measured atmospheric specific humidity. Errors in T_a alter the values of the Dalton number which is computed following the approach of Smith (1988). The 80% humidity assumption can cause large errors in regions where the surface layer is strongly stable stratified. If conditions are more unstable than assumed errors in the transfer coefficients are in the order of 10% for moderate wind speeds (Schulz et al., 1997) and much lesser for high wind speeds because the stability dependence is not longer important.

The derivation of retrievals for sea surface temperature from VIRS data; air specific humidity and surface wind speed from TMI data is described in detail in Schluessel and Albert (2000). The following three small sections give an overview over the retrievals and their validation. The basic strategy inherent to all three retrievals is that they are constructed from radiative transfer simulations for oceanic/atmospheric conditions that are assumed to be representative for the variability of the relevant atmospheric absorbers and surface states. Before any further analysis noise is added to the simulation to represent the radiometric instrument noise. The algorithms are then derived by statistical means (e.g. regression or neural network) from the simulated radiances and the representative data base.

3.1 Sea surface temperature

The infrared radiation transport model for simulating the VIRS radiances employs the *k*-distribution method of Hollweg (1993) to account for the selective absorption by gases and its overlapping. Quasi continuum absorption at the VIRS wavelengths 3.7, 10.8, and 12 μm is included following Bignell (1970) and Clough et al. (1989). The surface emissivity is described as a function of wind speed and incidence angle following Masuda et al. (1988) where the whitecap coverage is parameterised after Monahan and O'Muircheartaigh (1986).

The finally selected retrieval scheme for sea surface temperature uses a classical quadratic split-window approach during daytime and a linear triple-channel approach during nighttime both with an theoretical accuracy of ~0.4 K.

The retrieval coefficients were recalculated after comparison to the NDBC buoys where the differences between buoy and satellite measurements were highly correlated with the buoy measured surface temperature which was caused by an insufficient representation of the water vapour continuum absorption within the radiation transport model.

After this a standard deviation of 0.7 K and systematic differences of -0.36 K during nighttime and -0.14 K during daytime between buoy and satellite measurements were found. The systematic differences are within the expected differences caused by the bulk-skin temperature difference which is largest in cloud free areas during nighttime and less during daytime because the heating of the upper ocean through absorption of solar radiation leads to a smaller difference.

From the T_S values the surface saturation humidity q_S can easily be computed using the Magnus formula. The saturation humidity is then reduced by 2% to account for the salinity of the ocean water.

3.2 Air specific humidity

The estimation of the water vapour column content of the atmospheric boundary layer is justified by earlier work (Schulz et al., 1993; Schluessel, 1996). At most places over the ocean the water vapour column of the planetary boundary layer is closely correlated to the near surface specific humidity. Thus, q_a should be retrievable from TMI measurements. The retrieval algorithm found trying linear and non-linear multivariate analysis is a linear scheme employing 10, 19, 21, and 37 GHz brightness temperatures, the first two at both polarisations the latter two at vertical and horizontal polarisation, respectively. Non-linear approaches did not improve the retrieval quality very much because the weak non-linearity involved is superseded by the not explained variance in q_a. The theoretically accuracy for this algorithm is 1.2 g kg^{-1} which is only slightly worse than that of a conventional SSM/I algorithm which is at 1.1 g kg^{-1}. The reason for this is that the 21.8 GHz channel of the TMI is not as significant in the regression analysis as the 22.235 Ghz channel of the SSM/I. But the additional 10 GHz channel of the TMI balances the error almost to the same.

The validation of q_a retrievals versus NDBC buoys reveals large scatter with a standard deviation of 1.9 g kg^{-1}. The standard deviation for a conventional SSM/I retrieval in the same subtropical and tropical latitude belt is 1.8 g kg^{-1} (Schluessel et al., 1995). Thus, the new TMI retrieval is of comparable performance and can be used as the SSM/I retrievals.

3.3 Wind speed

In contrast to the humidity for the wind speed retrieval a non-linear approach (neural network) has been found to provide the most accurate estimates. The advantage of this approach comes to fruition in situations with increasing atmospheric liquid-water contents which can not be handled very good employing a linear regression.

After applying a correction to the TMI brightness temperatures because of a calibration error that is around 10 K at space temperature and zero around 300 K, the standard deviation between the NDBC buoy measurements and the TMI wind estimates is 1.7 ms^{-1}. The wind-speed histograms showed that the buoys provide more wind speeds less than 1 ms^{-1} and less wind speeds at wind speeds larger than 12 ms^{-1}. Schluessel and Albert (2000) speculated that the difference at low wind speeds is caused by adhesive friction of the anemometers so that they do not start turning at very low wind speeds. The difference at high wind speeds may exist because the anemometers at a measurement height of 5 m can be in wave troughs if high swell is present.

4. Comparisons to HOAPS and ECMWF

The retrievals and the bulk parameterisation scheme are applied to data from VIRS and TRMM during April 1998. All retrieval schemes are applied to the scan oriented data and the results are mapped on regular grids with a resolution of 0.5° 0.5°. The comparison data from the ECMWF analysis are on the same grid whereas the HOAPS data set has a resolution of 1° in latitude and longitude.

Figure 1 shows the monthly mean latent flux fields in W m^{-2} for all three data sources. The general structures are very similar with maximum fluxes in the subtropics and smaller fluxes along the ITCZ. The TRMM estimate shows smaller maximum values in the subtropics compared to HOAPS and ECMWF. The location of the maximum is in agreement with HOAPS which has its maximum in the northern hemispheric Pacific whereas ECMWF shows the maximum in the southern hemisphere in the Pacific and Indian Ocean. Along the ITCZ the TRMM estimate is much closer to ECMWF analysis than to the other satellite product. Large differences are also recognizable over the southern part of the Gulf Stream where the zone of high evaporation is narrower in the TRMM estimate.

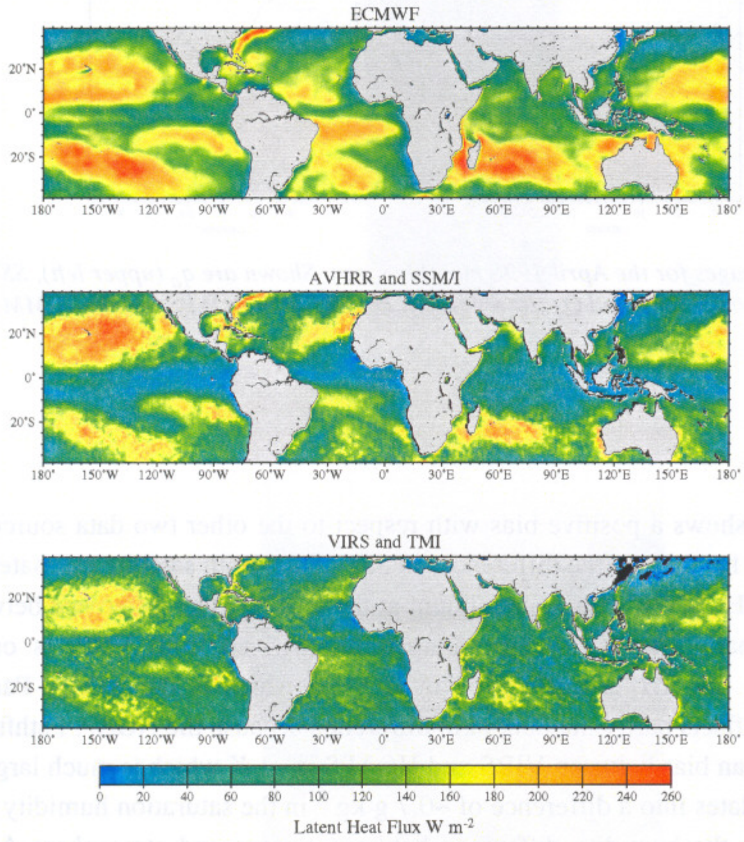

Fig 1: The monthly mean latent heat flux in W m^{-2} for April 1998 from three different data sources. Shown are values from ECMWF analysis (top), from HOAPS (middle), and TRMM (bottom).

To clarify more which parameter is responsible for this differences in Figure 2 the zonal averages of the monthly mean of *SST*, q_a, *U*, and Q_L are shown. The most prominent difference can be seen in the wind speed estimates. The TMI estimate shows higher wind speed throughout all latitude bands compared to the ECMWF analysis. Compared to HOAPS this differences become small north and south of 20°. This difference can be caused by the new TMI retrieval scheme which is also applicable in the case of light rain up to 5 mm h^{-1}. A comparison for collocated retrievals from TMI and SSM/I have not been done so that this question remain unanswered.

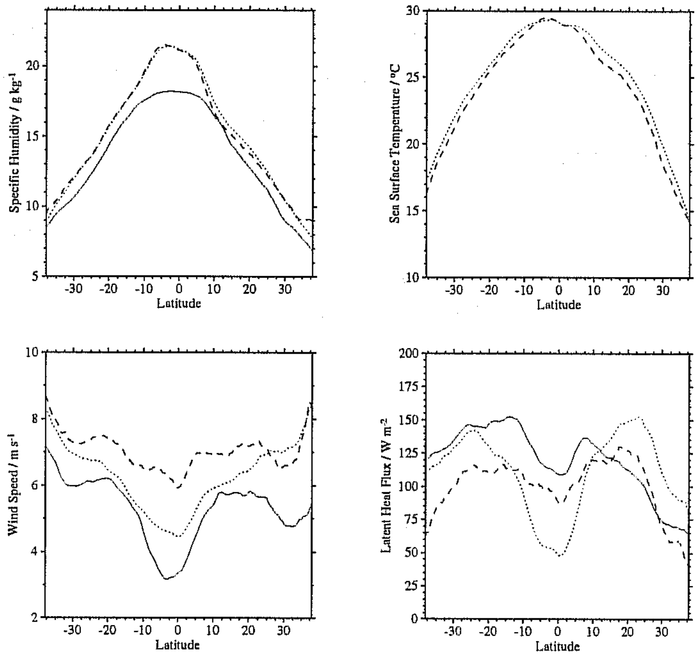

Fig 2: Zonal averages for the April 1998 monthly mean. Shown are q_a (upper left), SST (upper right), U (lower left), and Q_L (lower right). For SST only HOAPS and the TRMM estimate is shown.

Although the wind speed shows a positive bias with respect to the other two data sources the latent heat flux is smaller. The reason for this are the differences in *SST* an q_a. Both satellite estimates from q_a show a positive bias compared to ECMWF with its maximum at the equator. The difference between the satellite estimates is relatively small. The sea surface temperature derived from VIRS is outside the ITCZ systematically lower than the *SST* estimate used in HOAPS which is the NOAA Pathfinder product. Probably this difference reflects partly the bulk-skin difference because the NOAA Pathfinder product is a bulk *SST*. However the mean bias between VIRS and HOAPS is ~1 K which is much larger than the bulk-skin difference. This translates into a difference of ~0.7 g kg^{-1} in the saturation humidity at the surface. A difference of this order in the humidity difference between surface and atmosphere Δq accounts for a difference of 20 W m^{-2} in the latent heat flux. If at the same time the q_a estimate is higher as it is the case north and south of 35° than the difference in Δq is larger than one and the flux difference approaches 50 W m^{-2} as it can be seen at the most north and south bounded latitudes.

5. Conclusion

TRMM measurements are used to retrieve sea surface temperature, near surface specific humidity, and wind speed. A bulk parameterisation scheme is then used to compute latent heat flux estimates from the retrieved variables. The method is applied to data during April 1998 and the resulting monthly mean fields are compared to the ECMWF analysis and the monthly average from the HOAPS climatology. Major findings are:

- Sea surface temperature, near-surface air humidity, and wind speed can be retrieved from VIRS and TMI measurements with theoretically accuracies of 0.4 K, 1.2 g kg^{-1}, and 1.3 ms^{-1}, respectively.
- A comparison to bulk *SST* measurements from buoys showed a standard deviations of 0.36 K during night- and -0.14 K during daytime which reflects the skin effect at the sea surface. Comparisons for q_a and u revealed standard deviations of 1.7 m s^{-1} and 1.9 g kg^{-1}.
- Comparisons to monthly averages of ECMWF analysis showed a positive humidity and wind speed bias over all zonal bands with a maximum along the ITCZ that lead to a lower latent heat flux.
- Comparisons to HOAPS showed that the *SST* is cooler by ~1K which can't be explained by the bulk-skin difference. The near-surface specific humidity shows only a small negative systematic difference. Wind speed estimates from TMI are significantly higher along the ITCZ but of the same size elsewhere. The resulting latent heat flux is therefore larger along the ITCZ but lower in the subtropics.

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