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Latent Heat Flux and Ocean-Atmosphere Water Exchange

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Introduction

Starting from the pioneering studies of Liu and Niiler (1984) and Liu and Gautier (1990), spacebased data have been used to estimate the latent and net heat exchanges between the ocean and the atmosphere. Spacebased data provide more uniform coverage and better temporal variations than ship climatology. Although improvements have been made in the past decades by other investigators, considerable biases among various components of the exchanges remain, whether from ship measurements, satellite data, or numerical models. Recently, we have made major improvements in estimating high-resolution evaporation (E) and the integrated moisture advection (Θ). The divergence of Θ is equal to E-P, where P is the precipitation, when averaged longer than a few days. Achieving closures on the water balance in the atmosphere and the heat and mass balance in the ocean helps us to validate our results.

Methodology

The computation of the moisture transport integrated over the depth of the atmosphere

$$\Theta = \int_0^{p_s} q\mathbf{u}\,dp \qquad (1)$$

where p is the pressure and p_s is the pressure at the surface, requires the vertical profile of specific humidity (q) and wind vector **u**, which are not measured by spacebased sensors with sufficient resolution. Θ can be viewed as the column of water vapor,

$$W = \frac{1}{g}\int_0^{p_s} q\,dp \qquad (2)$$

advected by an effective velocity $\mathbf{u}_e$, so that $\Theta = \mathbf{u}_e W$, and $\mathbf{u}_e$ is the depth-averaged wind velocity weighted by humidity. Bold symbols represent vector quantities, and g is the acceleration to gravity.

W has been measured rather accurately by microwave radiometers. Improved methods were developed to related $\mathbf{u}_e$ to the equivalent neutral wind measured by QuikSCAT, $\mathbf{u}_s$, based on neural network (Liu and Tang, 2005) and to $\mathbf{u}_s$ and cloud-drift winds at 850 mb, based on support vector regression (Xie et al. 2007). The latest method significantly reduces both mean and standard deviation of the difference between Θ derived from the statistical model and from rawinsonde observations, from synoptic to seasonal time scales. Surface latent heat flux and E could be computed by removing P from $\nabla\cdot\Theta$.

We pioneered the method of estimating E, through bulk parameterization (e.g., Liu and Niiler 1984; Liu et al. 1994) two decades ago, using only spacebased observations. In bulk parameterization, E depends on surface wind speed, sea surface temperature (SST), and near surface humidity. Mircrowave radiometers measure wind speed, SST, and W. Surface humidity was first related to W through a statistical relation by Liu (1986). The rationale is that the vertical distribution of humidity is sufficiently coherent at low frequency (Liu et al., 1991). We are also improving and validating a method to retrieve E directly from the measured radiances, as first demonstrated by Liu (1990).

There were considerable differences among many precipitation data products in the past, but continuous improvement has put them closer to each other. Standard products from the Tropical Rain Measuring Mission (TRMM) (Kummerow et al. 2000) were used in this study.

Conservation Principles

While sufficient coverage and resolution of Θ and E can be best achieved from the vantage point of space, the validation of spacebased measurements has always been difficult because there is a lack of appropriate standards. While various components of ocean-atmosphere water and heat exchanges, including Θ and E, have been validated through point comparison with in situ measurements, useful scientific application may be the best validation of their usefulness. The closure of water and heat balances is a good way of validation, besides the characterization of the water and energy cycles.

Figure 1 shows that the annual mean of $\nabla\cdot\Theta$ bears similar large-scale features as that of E-P, over the ocean between 40°S-40°N. The agreement, not only in geographical variation but also in magnitude of the two terms, derived from separate methods, is extremely encouraging, and it is the best validation of both methodology and satellite observations. The agreement in intraseasonal time scales at two typical locations is evident in Figure 2. The agreements in the annual cycle and the semi-annual cycles are also shown in the tropical and equatorial regions respectively.

GRACE (Gravity Recovery and Climate Experiment) is a geodesy mission to measure Earth's gravity field, but the variation of the gravity field are largely the result of the change of water storage. Using GRACE mass change rate (∂M/∂t), Θ, and climatological river

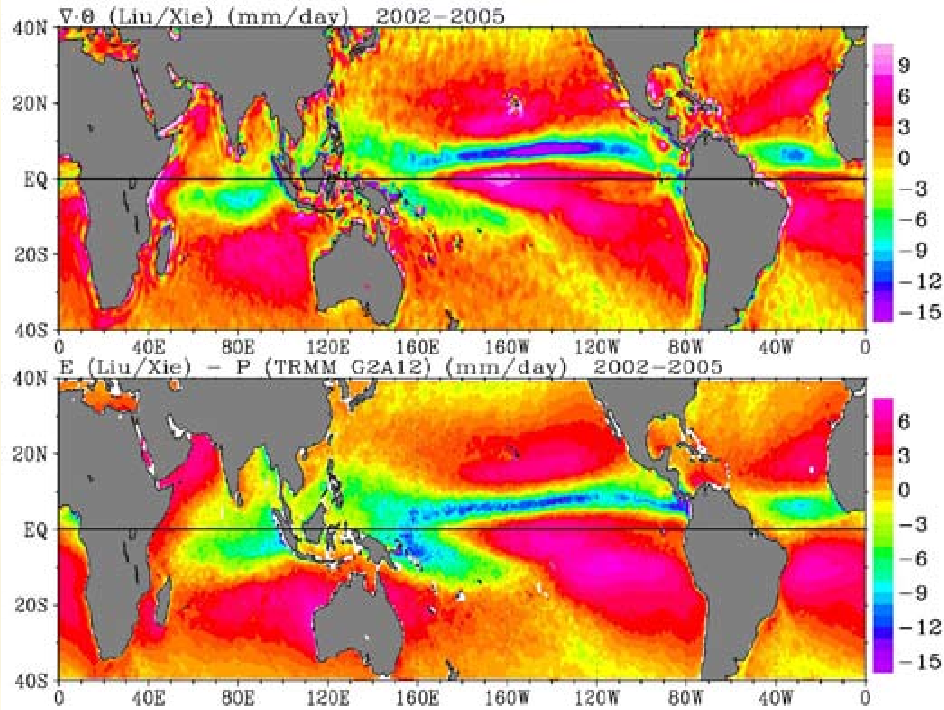

Figure 1. Annual mean of (a) ∇·Θ and (b) E-P in mm/day, averaged from 2000-2004, derived from QuikSCAT, SSM/I, and TRMM Microwave Imager (TMI).

discharge (R), Liu et al (2006) first demonstrated the continental water balance in South America. Figure 3 shows ∂M/∂t integrated over all ocean area, balances ∇ · Θ integrated over the same ocean area minus the line-integral of R over all coastline, both in magnitude and in phase.

If the change of heat storage in the ocean is negligible in long-term average, the heat exchanges with the atmosphere has to balance the heat divergence according to the conservation principle. For an ocean basin, such as the Atlantic or the Pacific, bounded by a latitude circle in the south and the continental mass in the north, the area integral of surface heat flux would give the time varying meridional heat transport (MHT) in the ocean. The large uncertainties in long term annual mean of MHT compiled in past studies are clearly demonstrated in Figure 4. In a preliminary study, the MHT computed from our spaced surface heat flux (red line) falls within

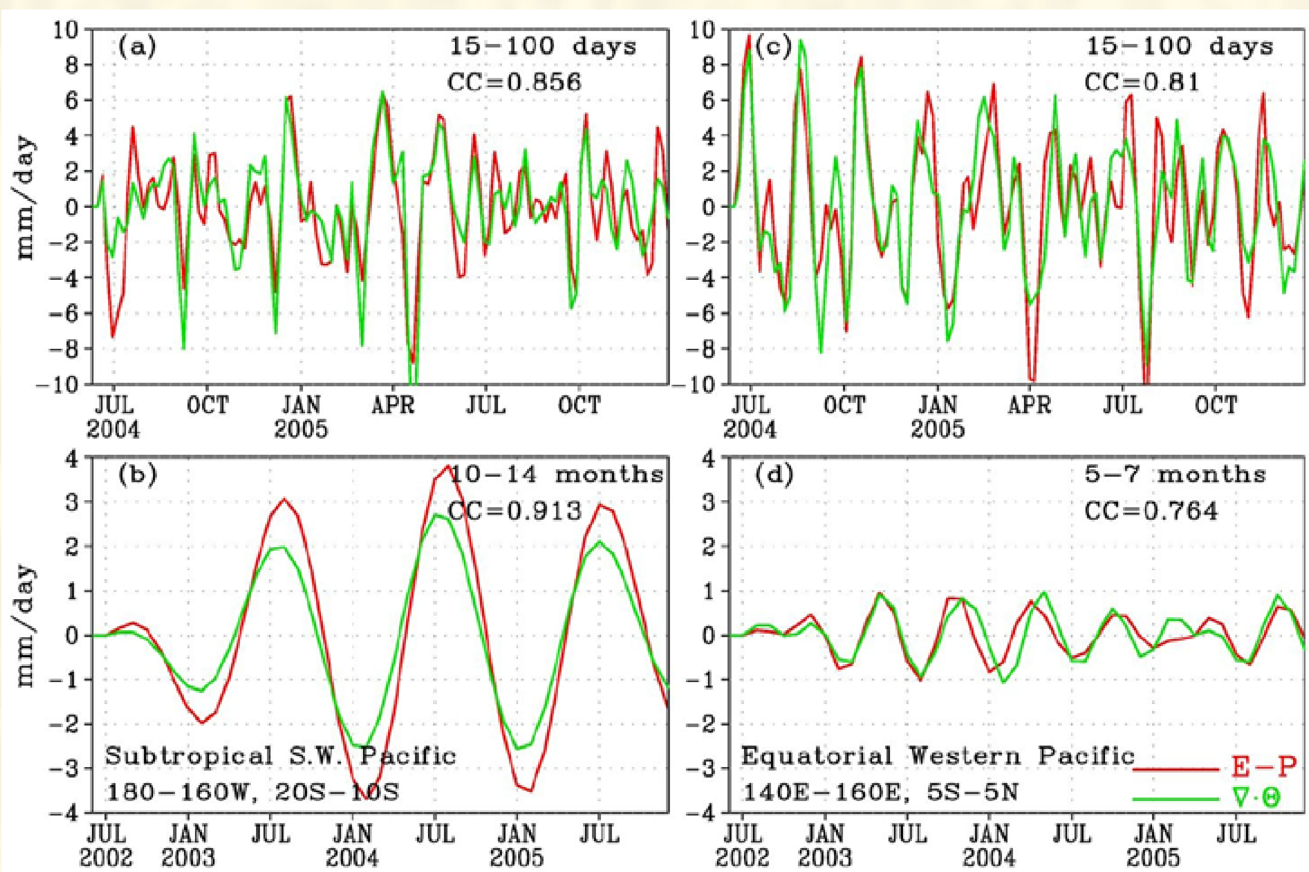

Figure 2. Band-pass filtered time series of ∇·Θ (green curve) and E-P (red curve) over South Pacific convergence zone for (a) 15-100 days, (b) 10-14 months, and over equatorial western Pacific for (c) 15-100 days, (d) 5-7 months.

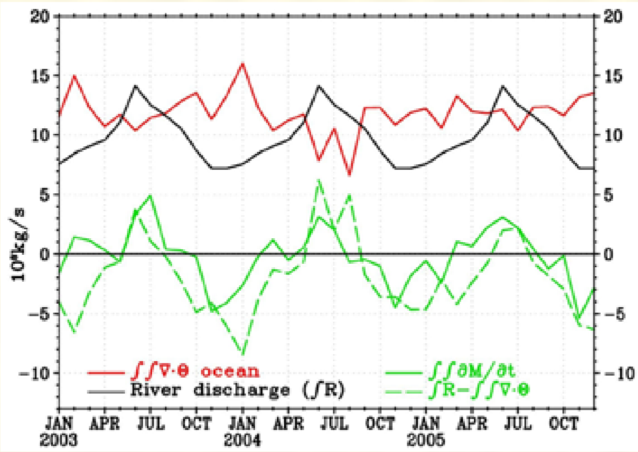

FIGURE 3. ANNUAL VARIATION OF HYDROLOGIC PARAMETERS AVERAGE OVER THE GLOBAL OCEAN: MASS CHANGE RATE $\iint \partial M/\partial t$ (SOLID GREEN LINE) AND $\iint \nabla\cdot\Theta$ (RED LINE), SUM OF CLIMATOLOGICAL TOTAL RIVER DISCHARGE ACROSS ALL COASTLINE $\int R$ (SOLID BLACK LINE), AND $\int R - \iint \nabla\cdot\Theta$ (DASHED GREEN LINE).

the large scatter of the old results. Our MHT is lower than those from the simulation of the Estimating the Circulation and Climate of the Ocean (ECCO) model (Fukumori 2002) (green line) between the equator and 30°N and higher than ECCO between 30°N and 50°N. It agrees with ECCO surprisingly well south of the equator.

Conclusion

Using spacebased estimation of E and Θ, we have demonstrated the approximate atmospheric water balance both in magnitude and in phase, from intraseasonal to annual time scales, the mass balance of global ocean in annual variation, and the heat balance of the Atlantic Ocean in the annual mean. The agreements with major conservation principles show the advances we have made in synergistic application of spacebased measurements to estimate ocean-atmosphere exchanges.

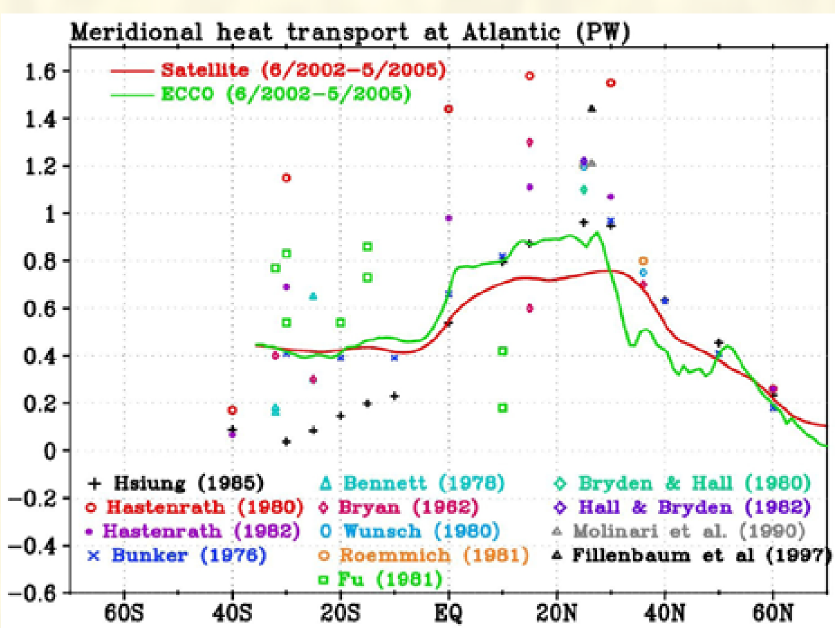

Figure 4. Comparison of annual mean MHT in the Atlantic as a function of latitude. Red curve is calculated using the surface heat flux from satellite observations. The green curve is computed from ECCO data. Values marked by various symbols and colors are from past studies, derived either from the surface heat flux or hydrographic measurements.

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