DIRECT RETRIEVAL OF OCEAN SURFACE EVAPORATION AND LATENT HEAT FLUX FROM SPACBASED OBSERVATIONS

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Abstract

Ocean surface evaporation and the latent heat it carries are the major components of the hydrologic and thermal forcing on the global oceans. However, there is practically no direct and continuous in situ measurement. The Tropical Rain Measuring Mission (TRMM) provides the opportunity to improve the spacebased estimation of evaporation. An algorithm for retrieving evaporation directly from the radiances observed by the TRMM Microwave Imager and its validation results are described. The method can be extended, in the future, to observations from the Advanced Microwave Scanning Radiometer, and retrospectively to observations by the Special Sensor Microwave/ Imager.

1. Introduction

The computation of latent heat flux (LH) by the bulk aerodynamic method [e.g., Liu, 1979] requires sea surface temperature (SST), wind speed (U), and specific humidity (Q),

$$LH = LC \rho U (Q_s - Q) \tag{1}$$

where L is the latent heat of vaporization, ρ is the surface air density. Q_s is the specific humidity at the interface, usually taken to be the saturation humidity at sea surface temperature (SST) multiplied by a factor of 0.98 to account for the effect of salt in the water. U and Q should be measured in the atmospheric surface (constant flux) layer, usually taken at a reference level of 10m. Over the ocean, U [e.g., Goodberlet et al., 1990; Wentz, 1997] and SST [e.g., Reynold and Smith, 1994; Wentz et al., 2000] can be measured quite accurately, but not Q. Spaceborne microwave radiometer, however, can measure the column-integrated water vapor (W) quite well [e.g., Alishouse, 1990; Wentz, 1997]. A method of estimating Q and LH over the ocean using satellite data was proposed by Liu and Niiler [1984]. It is based on an empirical relation between *W* and Q on a monthly time scale over the global ocean [Liu, 1986]. The physical rationale is that the vertical distribution of water vapor through the whole depth of the atmosphere is coherent for periods longer than a week [Liu *et al.,* 1991]. The relation does not work well at synoptic and shorter time scales and also fails in some regions during summer when compared with ship data and operational products of numerical weather prediction (NWP) [Liu, 1988; Liu *et al.,* 1992]. The relation has also been scrutinized in a number of studies [*e.g.,* Hsu and Blanchard, 1989; Eymard et al., 1989; Esbensen *et al.,* 1993; Jourdan and Gautier, 1994]. They either saw the cup half-full and suggested that the relation could be extended to instantaneous observations, or saw the cup half-empty and highlighted the high frequency and regional deficiencies of the relation. Modification of this method by including additional geophysical parameters or empirical orthogonal functions (EOF) as estimators, or use artificial neural network instead of statistical regression, have been proposed [*e.g.*, Wagner *et al.*, 1990; Cresswell *et al.*, 1991; Miller and Katsaros, 1991; Chou *et al.*, 1995; Jones et al., 1999], with various degrees of improvement but no revolutionary changes or significant impact. At present, we are able to discern the annual cycle and ENSO variations of LH over most of the global ocean; and Liu et al. [1994] demonstrated the oceanic responses in term of SST tendency in annual and interannual time scales.

2. Direct Retrieval

Liu [1990] suggested two possible improvements in LH retrieval. One suggestion was to obtain information on the vertical structures of humidity distribution and the other was to derive a direct relation between LH and the brightness temperatures (BT), the equivalent black body radiation, measured by the radiometer. This study addresses the second suggestion.

The Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus-7 launched in 1978 measures at five frequencies (6.6, 10..7, 18, 21, and 37 GHz) and dual polarizations. From these channel observations, all the three geophysical parameters needed to compute LH: U, SST, and *W*, can be retrieved [Wilheit and Chang, 1980]. Liu [1990] proposed and demonstrated the feasibility of retrieving LH directly from the measured radiances. Such method may improve accuracy in two ways. The first is to by-pass the uncertainties related to the bulk parameterization techniques. The second is to mitigate the magnification of error caused by multiplying inaccurate measurement of U with inaccurate measurements of Q and Q_s in the bulk formula (1). Liu [1990] used coincident BT values observed by the SMMR and LH computed from ship data (after quality selection) on monthly and 2° latitude by 2° longitude scales, and established a global relation (algorithm) through a multivariate linear regression (MVLR). While SMMR measures at 10 channels, only 6 channels were identified as significantly useful in estimating LH. The meridional variation of latent heat flux compares reasonable well with those from ship data shown in Fig. 1, from Liu [1990]. The comparison was performed on a data set different from those used in the derivation of the algorithm.

The Special Sensor Microwave / Imager (SSM/I), which is the operational microwave radiometer that followed SMMR, operates at 19, 22, 37, and 85 GHz in dual polarizations, (except for 22 GHz, which has only vertical polarization). It lacks the low-frequency channels, which are sensitive to SST, making direct retrieval of LH from BT alone unfeasible. Because of this handicap, we have not pursued direct retrieval for the past decade. The Microwave Imager on the Tropical Rain Measuring Mission (TMI), which was launched near the end of 1997, includes low frequency measurements (10.7 GHz) sensitive to SST. Direct retrieval of LH has become more feasible. The Advanced Microwave Scanning Radiometer (AMSR) which will have more channel than TMI, will be launched on the NASA EOS platform, Aqua, at the end of 2000, and on ADEOS-2 at the end of 2001, making continuous direct retrieval of LH attractive.

To extend the direct-retrieval algorithm developed for monthly average over 200 km area [Liu, 1990], to instantaneous satellite measurements, collocated values BT and LH, covering a wide spectrum of environmental conditions are needed. One approach is to simulate the radiance at the frequencies observed by TMI through a radiative transfer model using ocean surface parameters and atmospheric temperature and humidity profiles produced by the reanalysis of the European Center for Medium Range Weather Forecast (ECMWF). From the same ECMWF data set, coincident LH can be computed using a surface layer turbulent transfer model [e.g., Liu et al., 1979]. Liu et al. [1999], shows that the SSM/I BT simulated by a radiative transfer model, using atmospheric soundings from a Japanese research ship, have negligible bias and root-mean-square differences of about 1°K, when compared with observations by SSM/I. The radiative transfer model used in this demonstration uses a combination of atmospheric absorption by Liebe [1989] and ocean surface emission by Wentz [1998], and yields the best results among a number of models we have examined. A total of half a million profiles sub-sampled from global ocean covering one-year time span were used in this feasibility study. The simulated data set is then binned in the multi-dimension environment variable space to examine the sensitivities of BT to LH. Since those sensitivity studies are based on ECMWF profiles, no artificial or unrealistic constrains was used. The results of this sensitivity study was used to identify functions of BT which varies more or less linearly with LH.

The use of simulated BT is based on our confidence in the radiative transfer model and the integrity of ECMWF reanalysis in representing the radiative and hydrologic balance of an atmospheric column. Alternately, we collocated the BT measurements by TMI and surface flux derived from the bulk parameters produced by the reanalysis of ECMWF data. The advantage is to by-pass the uncertainties of the radiative transfer model but the disadvantages include the incorporating the known deficiencies of ECMWF model in representation boundary-layer processes, particularly over the tropical oceans, the likelihood of mis-location of marine storms, and the lack of spatial details. We have examined the use both sets of data to develop our retrieval algorithm.

We also have two approaches to derive the relation between BT and LH. The first is MVLR used by Liu [1990], but relating LH both to BT and to functions of BT that vary linearly with LH [e.g., Alishouse et al., 1990; Wilheit et al, 1980]. The second approach is to use the multi-layer perception of the artificial neural network (ANN) [Jones et al., 1999] . The first method is simple and explicit. The second method is useful in the case where a relationship is suspected , but the actual form of this relation is unknown; it is a good way to take care of the possible non-linearity between BT and LH.

SSM/I has provided continuous measurements over the global ocean for 13 years. Recently, several DMSP satellites have been in orbit at the same time, providing excellent coverage. To take advantage of this long time series and good coverage, we are exploring improvement of LH estimation from SSM/I data using a partial direct retrieval. The methodology will be similar to those used for TMI, except that operational SST data will be used as an estimator in additional to BTs.

3. Validation

Validation of the LH is very difficult because there are very few direct measurements. Measurements are made only under carefully designed experiments in limited locations for short periods of time. LH can also be derived through bulk parameterization schemes (with assumption and uncertainties), using mean parameters. Mean parameters measured from moored buoys usually have higher quality and with less platform interference than reports from merchant ships. In situ measurements are usually time averages (eddy correlation method for LH usually produce 20 minutes averages) at a single location, while satellite measures almost instantaneous spatial average (over footprint size). Validation exercises are bounded by the validity of the Taylor Hypothesis. Fig. 2 shows the locations of field campaign where latent heat flux was directly measured, and also the distribution of moored buoys where good quality bulk parameters have been measured. These data are being used to select a numbers of exploratory algorithms coming out of our studies.

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References

Alishouse, J.C., S. Snyder, J. Vongsathorn, and R.R. Ferraro, 1990: Determination of oceanic total precipitable water from the SSM/I. *IEEE Trans. Geosci. Remote Sens.*, **28**, 811-822

Chou, S.H., R.M. Atlas, and J. Ardizzone, 1995: Estimates of surface humidity and latent heat fluxes over oceans from SSM/I data, *Mon. Wea. Rev.*, **123**, 2405-2435.

Cresswell, S., E. Ruprecht, and C. Simmer, 1991: Latent heat flux over the North Atlantic Ocean-A case study. *J. Appl. Meteor.*, **30**, 1627-1635.

Goodberlet, M.A., C.T. Swift, J.C. Wilkerson, 1990: Ocean surface wind speed from the Special Sensor Microwave/ Imager (SSM/I). *IEEE Trans. Geosci. Remote Sens.* **28**, 823-828.

Esbensen, S.K., D.B. Chelton, D. Vickers, and J. Sun, 1993: An analysis of errors in Special Sensor Microwave Imager evaporation estimates over the global oceans" *J. Geophys. Res.*, **98**, 7081-7101.

Eymard, L., C. Klapiz, and R. Bernard, 1989: Comparison between Nimbus-7 SMMR and ECMWF model analyses: the problem of the surface latent heat flux. *J. Atmos. Oceanic Tech.*, **6**, 866-881.

Hsu, S.A., and B.W. Blanchard, 1989: The relationship between total precipitable water and surface-level humidity over the sea surface: a further evaluation, *J. Geophys. Res.*, **94**, 14539-14545.

Jones, C. P. Peterson, and C. Gautier, 1999: A new method for deriving ocean surface specific humidity and air temperature: an artificial neural network approach. *J. Applied Meteor.*, **38**, 1229-1245.

Jourdan, D. and C. Gautier,1994: Comparison between global latent heat flux computed from multi-sensor (SSM/I and AVHRR) and from in-situ data, *J. Atmos. and Oceanic Tech,* **12**, 46-72.

Liebe, H.J., 1989: MPM-An atmospheric millimeter-wave propagation model, *Int. J. Infrared and Millimeter Waves*, 10, 631-650.

Liu, W.T., K.B. Katsaros, and J.A. Businger, 1979: Bulk parameterization of air-sea exchanges in heat and water vapor including the molecular constraints at the interface. *J. Atmos. Sci.,* **36**, 1722-1735

Liu, W.T., and P.P. Niiler, 1984: Determination of monthly mean humidity in the atmospheric surface layer over oceans from satellite data, *J. Phys. Oceanogr.*, **14,** 1451-1457.

Liu, W.T., 1986: Statistical relation between monthly precipitable water and surface-level humidity over global oceans, *Mon. Wea. Rev.*, **114**, 1591-1602.

Liu, W.T., 1988: Moistures and latent heat flux variabilities in the tropical Pacific derived from satellite data. *J. Geophys. Res.*, **93**, 6749-6760 and 6965-6968.

Liu, W.T., 1990: Remote Sensing of surface turbulence flux, Surface Waves and Fluxes,Vol. II,. G.L. Geenaert and W.J. Plant (eds), Kluwer Academic, Chapter 16, 293-309.

Liu, W.T., W. Tang, and P.P. Niiler, 1991: Humidity profiles over ocean, *J. Clim.*, **4**, 1023-1034.

Liu, W.T., W. Tang, and F. J. Wentz, 1992: Precipitable water and surface humidity over global oceans from SSMI and ECMWF, *J. Geophys. Res.*, **97**, 2251-2264.

Liu, W.T., A. Zheng, and J. Bishop, 1994: Evaporation and solar irradiance as regulators of the seasonal and internanual variabilities of sea surface temperature, *J. Geophys. Res.*, **99**, 12623-12637.

Liu, W.T., L. Li, and W. Tang, 1999: Sensitivity of space-based microwave radiometer observations to ocean surface evaporation. *Proc., IGARSS '99*, 2303-2305, IEEE

Miller, D.K., and K.B. Katsaros, 1991: Satellite-derived surface latent heat fluxes in a rapidly intensifying marine cyclone, *Mon. Wea. Rev.*, **120**, 1093-1107.

Reynolds, R.W., and T.M. Smith, 1994: Imporved global sea surface temperature analyses using optimum interpolation. *J. Climate*, **7**, 929-948.

Wagner, D., E. Ruprecht, and C. Simmer, 1990: A combination of microwave observations from satellite and an EOF analysis to retrieve vertical humidity profiles over the ocean", *J. Appl. Meteor.*, **29**, 1142-1157.

Wentz, F. J., 1997: A well-calibrated ocean algorithm for special sensor microwave/imager (SSM/I). *J. Geophys. Res.*, 102, 8703-8718.

Wentz, F.J., 1998: *Algorithm Theoretical Basis Document: AMSR Ocean Algorithm.* Technical Rept. 110398, Remote Sensing System, Santa Rosa, CA.

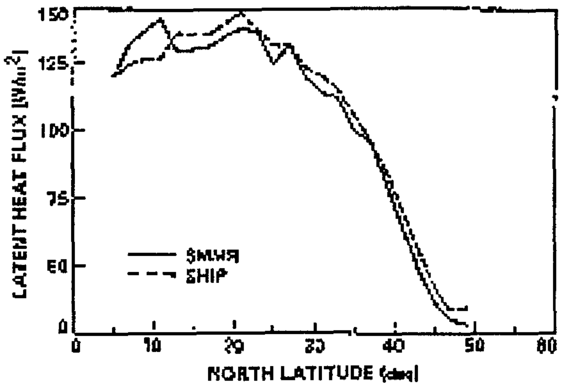
Wentz, F.J., 2000: Satellite measurements of sea surface temperature through clouds. *Science*, **288**, 847-850.

Wilheit, T.T., and A.T.C. Chang, 1980: An algorithm for retrieval of ocean surface and atmospheric parameters form the observations of the scanning multichannel microwave radiometer. *Radio Sci.*, 15, 535-544.

Figure Legends

Fig.1 Comparing zonal mean latent heat flux derived from ship reports and from Nimbus/SMMR brightness temperatures from 1982 (from Liu, 1990).

Fig.2 Location of long-term moorings and field campaigns, with measurements available for validation of spacebased latent heat validation.



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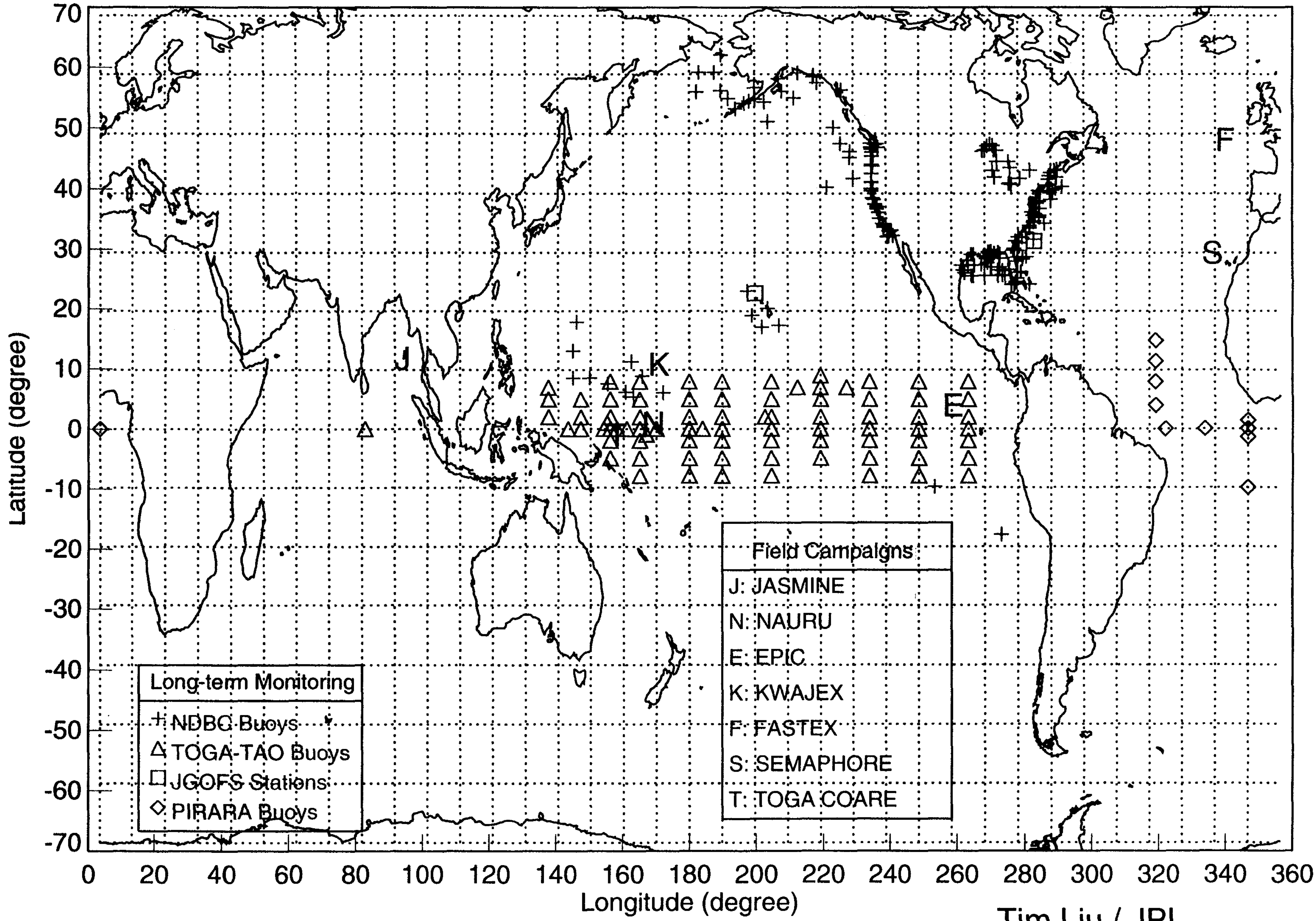

Latitude (degree)
Longitude (degree)
70
60
50
40
30
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10
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-10
-20
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-40
-50
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J
K
N
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S
Long-term Monitoring
+ NDBC Buoys
△ TOGA-TAO Buoys
□ JGOFS Stations
◇ PIRARA Buoys
Field Campaigns
J: JASMINE
N: NAURU
E: EPIC
K: KWAJEX
F: FASTEX
S: SEMAPHORE
T: TOGA COARE

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