

Air-sea flux estimates from satellite observations

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Received 23 May 1997; revised 9 December 1997

Bulk aerodynamic parameterisation is described for estimation of latent and sensible heat fluxes, with the method to obtain the near surface specific humidity, sea surface temperature (SST), near surface air temperature etc., by space borne observations. The accuracy of these parameters on the estimation of these fluxes is also given. The monthly variation of these fluxes by microwave radiometers like SSM/I are explained. The evaporation estimate as based on these satellite parameters is assessed by comparison with ship observations. Sensible heat exchange is also estimated and assessed.

Fluxes of heat and momentum at the sea surfaces together with radiative fluxes, control the formation and mixing of water and air-masses and are responsible for the dynamic and thermodynamic forcing of the oceans, and much of the atmosphere. Heat loss from the ocean changes the upper ocean stratification and modifies the ocean circulation. The large heat capacity of oceans and the relatively slow adjustments of ocean circulations act as a fly wheel on the atmospheric circulations. The amount of latent heat flux exchanged to the atmosphere is almost 15 times that of sensible heat flux over the tropical Indian Ocean. The computation of these fluxes is important, since they form as input to various global circulation models¹, particularly over tropics.

Though satellite observations are less vulnerable to sampling biases compared to ship observations, satellite observations are prone to errors resulting from atmospheric events and systematic biases. Hence the heat flux estimates using satellite observations are subjected to certain level of uncertainties. The possible major sources of uncertainties in the heat flux estimates by bulk method are the errors due to the differences in averaging method, error due to random sampling, sensor accuracy, scheme variation, error in observations used to formulate the bulk formulae. Since satellite observations are usually calibrated

with ground based measurement, the accuracy of ground based sensors have to be considered.

This paper elucidates show satellite data from different sensors can be used to compute heat flux over the air-sea interface.

Materials and Methods

Latent heat exchanges

The latent heat flux exchanged from the ocean to the atmosphere is parameterized in terms of wind speed (V), difference in specific humidity at sea surface and air ($q_s - q_a$). The typical errors associated² with surface meteorological parameters (from ship) are 1°K in T_a and T_s , 2 m sec^{-1} in V , and 3 g kg^{-1} in ($q_s - q_a$). The most accurate estimate of air-sea fluxes are probably produced in field experiments, but are usually available only at specific points for limited period of time. Differences in time and space scales between point observations and gridded values from analysis or satellite estimates can complicate the comparison.

The bulk parameterization equation may be written as³:

$$\text{Latent heat flux } L_a = d C_D L (q_s - q_a) V$$

where, d is the density of air (1.2 kg m^{-3}), C_D -drag coefficient, q_s -saturation specific humidity (g kg^{-1}), q_a -specific humidity at air temperature (g kg^{-1}), V -wind speed (m sec^{-1}), L -latent heat of vaporization

($2.45 \times 10^6 \text{ J kg}^{-1}$). The spaceborne sensors can measure wind speed (V), and SST, but not T_a and q_a .

The drag coefficients are functions of stability, measurement height, wind speed and sea state⁴. At higher wind speeds the production of spray might change the drag coefficients. The neutral values of C_D is within the range of 1.05 to 1.2×10^{-3} .

In future Indian satellite IRS-P4 will have a sensor MSMR (multi-frequency scanning microwave radiometer), providing dual polarized brightness temperatures at 6, 10, 18, and 21 GHz measurements, which can be used to compute the latent heat fluxes.

Sensible heat exchanges (S_h)

This also can be parametrized in terms of surface wind (V), and difference in air and sea surface temperature ($T_s - T_a$) by bulk parameterization equation.

$$S_h = d C_D C_p V (T_s - T_a)$$

where V -wind speed, T_a -surface air temperature, T_s - sea surface temperature, C_p - specific heat of air at constant pressure, C_D - drag coefficient (explained earlier), d - is the density of air (1.2 kg m^{-3}). The various parameters used in the bulk parametrisation for computation of heat fluxes are further explained in the sub-sections.

Results and Discussion

Sea surface wind /wind stress

Since the fluxes are proportional to wind speed a target accuracy of 10% is required. Among satellite sensors, at present the most accurate ocean surface winds (both speed and direction) are given by microwave wind scatterometers⁵ (as in the case of ERS-1, which has 3-beam scatterometer which gives better accuracy than 2-beam SEASAT scatterometer). They have an accuracy of 2 m/sec in speed and 20° in direction. Cloud vector motion winds at 900 mb is reduced to surface by applying planetary boundary layer wind shear⁶. The accuracy of these winds when sufficient cloud vector motion winds are available is of the order of 2 m sec^{-1} . Conventionally the stress ' τ ' is related with wind data by the bulk aerodynamic formula

$$\tau = d C_D V^2$$

where d is the density of air and C_D the drag coefficient, which is assumed to be a function of

wind speed and atmospheric boundary layer stability.

In the case of scatterometer the backscattering is caused by the wind induced capillary waves. Breaking provides a second mechanism of momentum transfer. Thus, scatterometer is more directly measuring surface wind stress and so it is more useful than *in-situ* measurements⁷.

The wind stress during monsoon time is depicted⁸ in Fig. 1. In the region of cross equatorial low level jet (off Somalia coast), the meridional wind stress is of the order of $15 \times 10^{-2} \text{ kg m}^{-1} \text{ sec}^{-2}$ during south-west monsoon onset. The meridional and zonal wind stress south of Arabian Sea and Bay of Bengal in equatorial Indian Ocean are also shown in the Fig. 1.

Specific humidity and surface air temperature

Satellite does not directly provide specific humidity and air temperature at ocean surface. In the region of intense moisture convergence as in the case of monsoon depressions, lows and cyclones, it is required to know the moisture profile. The specific humidity at ocean surface is derived using a technique of variable scale height of water vapour from NOAA/TOVS (Tiros Operational Vertical Sounder). The specific humidity at ocean surface is also calculated derived using global relation⁹ and microwave data which is applicable in a monthly time scale. Recently a retrieval method was developed for estimation of the near surface specific

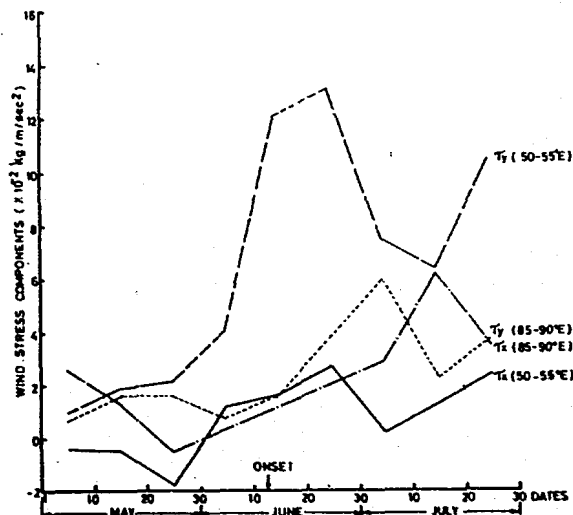


Fig. 1—Zonal and meridional wind stress (equatorial belt: 0°N - 6°S) during south-west monsoon onset of 1979.

humidity with an accuracy of 1.2 g kg^{-1} using the SSM/I 19, 22, 37 GHz brightness temperature^{10,11}

The NOAA/TOVS, gives precipitable water vapour in three different layers (1000-700, 700-500 and 500-300 mb). It also provides layer mean temperature in 15 layers of which (1000-850, 850-700 mb) provided by NOAA sounding data is used. Using the average pressure between the two levels, the average density 'd' was determined. Then using hydrostatic equation $dp/dz = -gd$ the lapse rate ' τ ' was also found from dt/dz ^{12,13}.

Surface air temperature

Present day satellite do not give surface air temperature. The air temperature has been calculated using statistical method¹⁴, where a direct relation between T_s and W (precipitable water vapour) has been obtained. Recently anew algorithm, was also developed whereby the near-surface air temperature is determined from the physical properties obtained by satellite measurements¹⁵.

In the present paper the lapse rate was used with layer temperature T_1 and average height 'Z' of the 1st layer to get surface air temperature as T_a from the equation⁶.

$$T_a = T_1 + \tau Z \quad \dots (2)$$

(This is useful in sensible heat flux calculation).

Specific humidity from NOAA/TOVS

As mentioned in the previous section, once the height of different pressure levels and total precipitable water vapour content in these layers are known, the scale height 'H' can be calculated assuming an exponential density profile. This can be determined⁶ as follows:

$$\text{Water vapour content } W_1 = d_0 \int \exp(-Z/H) dz \quad \dots (3)$$

(in 1000-700 mb layer)

$$\text{Water vapour content } W_1 = d_0 \int \exp(-Z/H) dz \quad \dots (4)$$

(in 700-500 mb layer)

where d_0 is the water vapour density at surface, and Z is the height. Taking the ratio of these two equations d_0 was eliminated, and was solved iteratively to get the scale height 'H', which with lower water vapour content we get, d_0 .

Specific humidity of air at surface,

$$q_a = d_0 / d_{air}$$

Saturated specific humidity at sea surface,

$$q_s = \frac{5}{8} \frac{e_s}{p - e_s}$$

$$e_s = T_s^A 10^{(B+C/T_s)}$$

$A = -4.928$, $B = 23.55$, $C = -2937.0$; T_s - sea surface temperature (provided by NOAA/AVHRR) data and P - sea level pressure.

The comparison of satellite derived humidity profile with radiosonde is depicted in Fig. 2. This indicates that the profile of specific humidity obtained from satellite data matches well with those of ship radiosonde data. However using a constant scale height of water vapour (2 km), there is significant departure in specific humidity (of the order of 5 g kg^{-1}). In future the AMSU-A & B (Advanced Microwave Sounding Unit), will have better vertical resolution of atmospheric temperature and humidity profile.

Surface specific humidity (microwave satellite data)

Space borne microwave radiometers can measure total precipitable water vapour¹⁶ with an accuracy of 0.8 g kg^{-1} . A statistical relation between the monthly integrated precipitable water vapour (W) and specific humidity at surface (q_a) were derived using 17 years of radiosonde reports and 46 mid-ocean stations⁹. The relation is as follows (valid for monthly time scales).

$$q_a = 3.81872W + 0.1897219 W^2 + 0.1891893 W^3 - 0.07549036 W^4 + 0.006088244 W^5$$

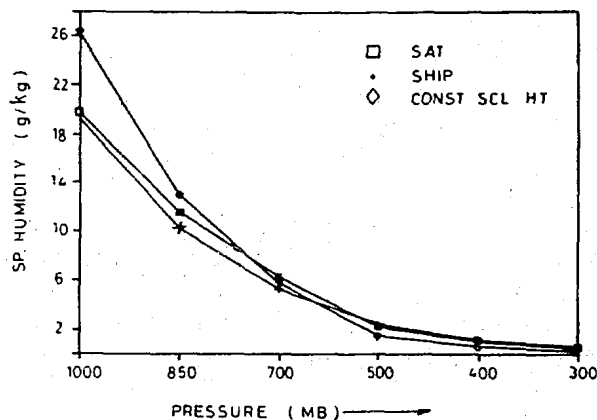


Fig. 2—Comparison of satellite derived humidity profile and radiosonde observed humidity profile at equator and 55°E.

An improved remote sensing technique for estimation of instantaneous specific humidity at surface using SSM/I microwave brightness temperature (19 H & V, 22 V and 37 V) is given as,

$$q_s = a_0 + a_1 \times w_1$$

where q is the near surface specific humidity (g kg^{-1}),

$$a_0 = -0.032 \text{ g/kg}, a_1 = 17.98 \text{ cm}^2/\text{kg}, \text{ and}$$

w_1 is given by

$$w_1 = b_0 + b_1 \times T_{19V} + b_2 \times T_{19H} + b_3 \times T_{22V} + b_4 \times T_{37V}$$

where, $b = -5.9339$; $b_1 = 0.03697$; $b_2 = -0.02390$, $b_3 = 0.01559$; $b_4 = -0.00497$

Adjustment of exchange coefficient (C_D)

Typical value of C_D is 1.2×10^{-3} . The drag coefficient C_D can be given as function of wind speed¹⁷

$$C_D = A + B \tanh(\text{SQRT}(V^2 - 4) \cdot C)$$

Large *et al.*⁶ has studied extensively on dependence of C_D and acceptable envelope of values of C_D as function of neutral stability and wind speed. The C_D is also a function of thermal stability.

This stability parameter^{6,18} (Richardson Index) was used to modify the drag coefficient. The C_D did make about 20% change in the heat exchange results. The latent heat flux thus computed were compared with MONEX data and was found to be within an accuracy of 25%. The scatter plot is shown in Fig. 3. The monthly latent heat flux computed from SSM/I and AVHRR data^{19,20} over Indian region is shown in Fig. 4. Just prior to onset of the monsoon (i.e. in May and June) the latent heat flux of the order of 360 watts m^{-2} is seen near Somalia coast.

Sea surface temperature (SST)

The physical basis for measurement of SST from space is the detection by a space borne sensors microwave or infra-red radiometers of the thermal energy emitted by the ocean surface. This is presently derived from multichannel algorithms from NOAA satellites. The sensor used is AVHRR (advanced very high resolution radiometer) which provides global data at 4 km resolution and also wherever ground stations are available at 1 km resolution. McIlain,²¹ has derived global coefficient for AVHRR by regression of satellite measurement

with measurement of geographically located fixed drifting buoys.

$$\text{SST}(\text{day}) = 1.0346 T_{11} + 2.58(T_{11} - T_{12}) - 283.21$$

$$\text{SST}(\text{night}) = 1.017 T_{11} + 0.97(T_{3.7} - T_{12}) - 276.8$$

where SST is in $^{\circ}\text{C}$ and T_i is the infra-red brightness (K) for channel "i". The day time algorithm does not use 3.7 μm channel due to high reflectance of the incident solar radiation in these channel.

Along track scanning radiometer (ATSR) onboard ERS-1 is a dual angle sensor at the same frequency, and is capable of improved accuracy, since estimation of wavelength dependency on atmospheric absorption is not required. The SST can be measured with an accuracy of 1.5 $^{\circ}\text{K}$ (0.5 $^{\circ}$ in certain regions) or better accuracy. The INSAT-VHRR is also useful for SST gradients (not absolute). The satellite derived SST is more relevant to air-sea interaction being the skin temperature observed from the emitted infra-red observation rather than "bucket temperature" as conventionally measured.

In case of cloudy observation microwave technique can give SST measurement, since absorption of surface radiation by atmospheric gases and clouds is much lower in microwave length. The SMMR has a dual polarized channels at frequencies (6-37 GHz)²² with 150 km resolution. Satellite gives a synoptic view of thermal patterns associated with upwelling, El-Nino, fronts, gyres, etc. In tropical region SST is the order of $\sim 26^{\circ}\text{C}$, SST error of 0.3 $^{\circ}\text{C}$ will produce a 10 w m^{-2} flux error for 10 m sec^{-1} wind.

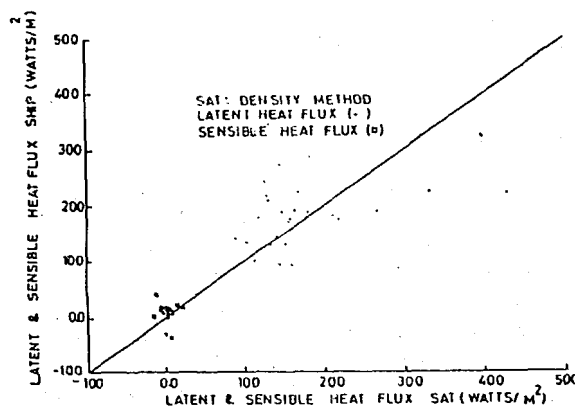


Fig. 3—Latent and sensible heat flux comparison (satellite v/s ship) May 1979.

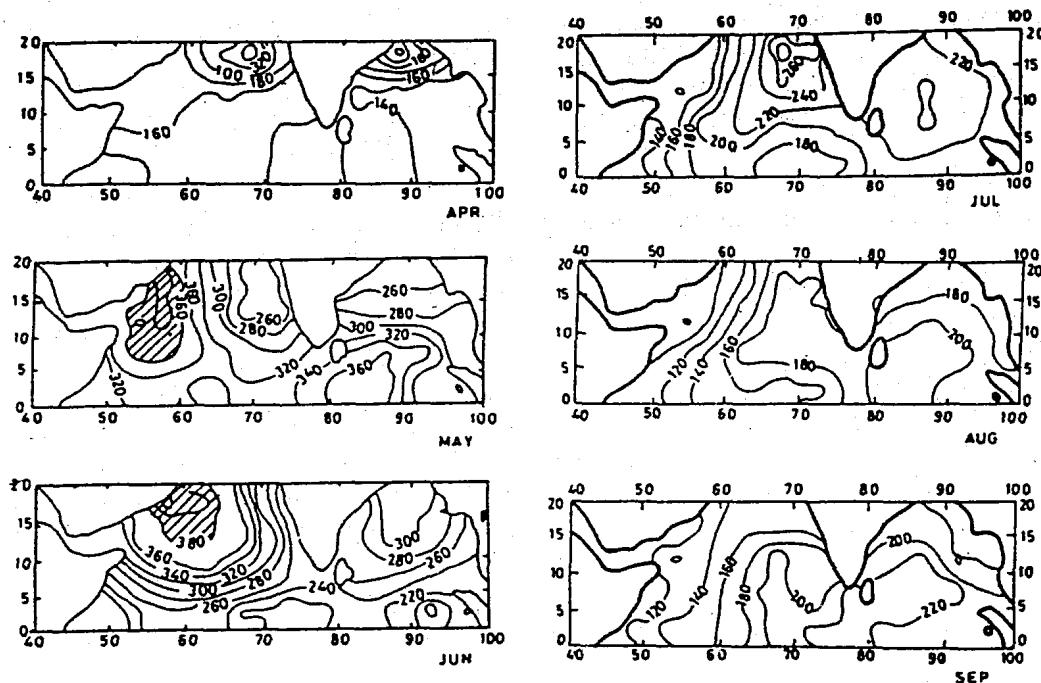


Fig. 4—Monthly mean latent heat flux field (W. m^{-2}) for the year 1988.

The sensible heat flux (S_H) calculated using MONEX data were compared with satellite data are shown in Fig. 3. The accuracy was within 35%. Another way of calculating sensible heat flux is by calculating Bowen's ratio ($B = S_H/L_H$) using ship data, along with latent heat flux from satellite data which, yielded a better accuracy of 30%.

Future sensors like AMTS (Advanced moisture and temperature sounder) and AMSU can give temperature profile with better accuracy. Especially AMTS has a sensor at ($4.123 \mu\text{m}$) which can directly give the air-surface δT which will be useful for sensible heat flux calculation.

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