THE USE OF SATELLITE DATA FOR INFERRING SURFACE FLUXES : APPLICATION TO THE VALIDATION OF GCM AND NWP MODELS

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Summary : To infer surface fluxes from satellite data with or without the aid of other meteorological information, many methods have been proposed. In particular, the surface radiation budget can be obtained over sea and over particular land areas with a rather good accuracy. On the contrary, the turbulent flux (heat, evaporation, momentum) retrievals are not still operational over any surface. Some of these methods, however, could constitute basis for a future use in the models.

1. INTRODUCTION

Modelling and monitoring the surface fluxes of heat, evaporation, momentum and radiation over the time and space scales relevant for climate and weather forecasting is not yet possible, due to the complexity of the physical system involved. Satellite remote sensing techniques can provide some surface and atmospheric parameters which are useful in monitoring either the surface fluxes or associated quantities over various time scales. Many methods have been proposed to use satellite data for determining surface fluxes, some of them including complex models of the atmosphere and the surface, whereas others are based on empirical relationships. Validation of these methods is generally achieved on a regional basis, because of the necessary data set. Few comparisons with GCM or weather forecasting model outputs have been done, and most of the satellite methods are not yet fully operational.

When looking for the surface energy budget, the relative importance of the various terms is different over land, sea and polar ice. Over land, heat, evaporation and radiation are nearly equally important, and the net budget is balanced at a daily scale. Over the ocean, the ocean-atmosphere interaction is governed by the stress, the net heat flux (sum of radiative, latent and sensible) and balance in fresh water (net of evaporation and precipitation). The necessary accuracy of each flux for climate or regional applications is therefore different over each surface.

We will first examine the radiative flux, then heat, evaporation and momentum flux retrieval methods. Then we will discuss the possibility to validate atmospheric models diagnosed fluxes using these methods.

2. RADIATIVE FLUXES

The net radiation is the sum of downward and upward fluxes in shortwave (0.3 - 4 µm) and longwave (4 - 100 µm). None of these quantities is directly accessible from satellite remote sensing due to the atmosphere. Thus many techniques have been developed to relate the satellite radiances (in visible and IR) to them. Most of them estimate separately the different components of the net radiative flux. The main problem is the determination of surface downwelling shortwave and longwave radiation. The net fluxes can be obtained, if additional informations about the effective surface temperature, emissivity and the surface albedo are available.

We will see successively the methods proposed for the retrieval of the shortwave and the longwave downward flux. The net fluxes will then be discussed. A review of these retrieval methods can be found in *Schmetz* (1989).

2. 1 Surface solar flux (SSF)

The radiation received at the top of the atmosphere (TOA) depends on the solar zemith angle, gas and aerosol absorption and scattering, clouds and surface reflectivity. As the atmosphere does not emit radiation in this frequency band, there is a relationship between the surface flux and the received radiation. The main problem is to evaluate the atmospheric absorption with a sufficient accuracy. *Ramanathan* (1986), using a GCM with a radiative transfer model to simulate the TOA and surface fluxes, found a strong linear correlation between the surface solar flux and the TOA flux (fig.1), both in monthly mean and hourly values, due to compensation between cloud absorption and water vapour below base (not reached by the solar flux when cloud occur). A linear relationship is also observed between the downward SSF and the planetary albedo, even if the cloudiness is not homogeneous (*Schmetz*, 1989).

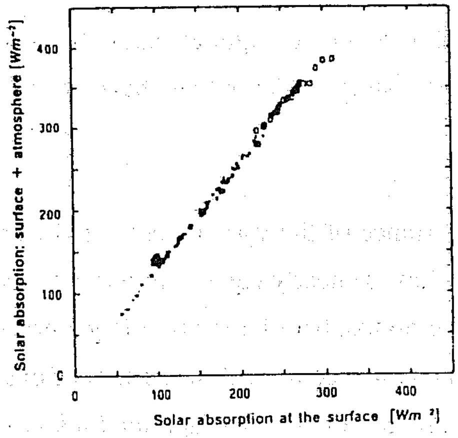


Fig. 1 Scatter plot of the solar system absorption (at TOA) versus solar surface absorption, from Ramanathan (1986) and Schmetz (1989). Results are monthly means obtained using the NCAR GCM over selected regions.

The retrieval of SSF from satellite radiances is based on the expression of the atmospheric radiative transfer, relating the TOA flux to the SSF. The proposed methods differ by their type and complexity : some of them include a full description of the radiative transfer processes whereas some others consist of simplified schemes, using a set of prescribed or parameterized parameters. An alternative to physical modelling is pure statistical relationships. An additional difficulty is that operational satellites (NOAA, geostationnary) do not measure the broadband incoming radiation, but a narrow-band value. *Ramanathan* (1986) noted that the spectral behaviour is very different at the surface and at TOA, due to the relative fraction of direct and scattered solar beam, varying with turbidity near the surface over the ocean, and depending on the vegetation spectral reflectivity. This problem, for calculating the planetary albedo, in particular, is not encountered with the ERB data, which are broadband.

The objective of physical methods is to simulate the radiative transfer processes (atmosphere plus clouds), to relate the surface solar flux to the satellite data. *Bishop and Rossow* (1991) described a full radiative transfer, taking into account surface and cloud parameters, and atmospheric profiles of all relevant quantities (water vapour, gases). Due to the difficulty to get the necessary inputs, many authors simplified the radiative transfer model by replacing some equations by parametrizations based on assumptions (cloud characteristics, in particular). They also often prescribe some quantities, as ozone or water vapour profiles, to make the method applicable to operational satellite data.

Several methods are derived from the one developed by *Gautier et al* (1980), applied to GOES/VISSR data. A clear sky simplified formulation is established (using a complete radiative transfer model), as a function of absorption coefficients of atmospheric constituents, solar zenith angle, and albedo. Under cloudy conditions, an additional term accounts for reflection and absorption by clouds. *Frouin et al* (1988a) applied and validated the model over ocean, at a regional scale. *Le Borgne and Marsouin* (1988) and *Brisson et al* (1993) derived from this approach an operational scheme, validated over selected land sites and sea.

Other modelling approaches are based on the use of sun-synchronous instead of geostationary satellites (*Darnell et al,* 1988). Their main problem is the occurence of clouds, time-dependent within the day (diurnal cycle), in particular in the tropics. Their advantage is the global coverage obtained with the same satellites. Data from ERB have permitted to directly obtain the planetary albedo, thus simplifying and improving calculations: *Frouin and Chertock* (1992) could estimate ths solar surface flux at a global scale, but needed the climatological variations of some parameters (ozone, among others). Using the ISCCP large data base, *Bishop and Rossow* (1991) benefited of both geostationary satellite data including cloud parameters and TOVS profiles, to calibrate a simple scheme, in comparison with a full radiative transfer model (using additional data from land surface type, and climatology).

The principle of statistical methods is a regression made between the measured surface solar flux and satellite radiances. Such a relationship can be calibrated using a first data set or model outputs before being applied. It can be simple, between the surface irradiance and the brightness, normalized to the extraterrestrial radiation, or directly the visible counts. *Li et al* (1993) established a linear relationship between the TOA flux and surface flux, based on radiative transfer calculations, and including solar zenith angle. They showed the independence of their method with cloud optical thickness and surface albedo, permitting to infer the net flux under overcast sky. *Cess et al* (1993) used ERBE data (ERB satellite and NOAA9) for cloudy and clear conditions, with colocated surface measurements. They verified the linear relationship between TOA and surface fluxes, and between the downward solar flux and the cosinus of the solar zenith angle.

2.2 Surface longwave flux

In this wavelength range, the atmosphere absorbs, emits and scatters radiation. The surface downward longwave flux (DLF) depends on the vertical profiles of temperature, gases and clouds, but the DLF is essentially dependent on the radiation from a shallow layer near the surface : using radiative transfer calculations, the lowest 10m was found to emit about 30% of the total flux (*Schmetz*, 1989). Cloud relevant parameters are cloud base height and temperature, cloud cover and emissivity. In contrast to the solar flux, the surface longwave flux is largely decoupled from the radiation at the top of the atmosphere (*Ramanathan*, 1986), as shown in Fig.2. Hence information is required for the near-surface temperature and humidity, cloud cover and emittance, and height and temperature of cloud base. This explains that the longwave flux retrieval is much more difficult than the solar flux retrieval.

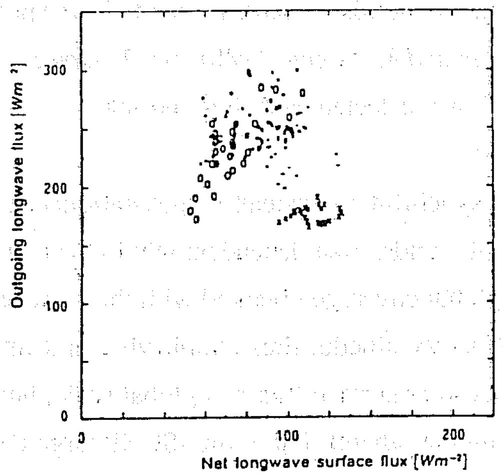


Fig.2 : as Fig.1, but for the longwave radiation.

Again, both statistical and physical approaches have been developed, but there is much less studies in the litterature than for the shortwave radiation.

Physical methods are based on radiative transfer models, using atmospheric profiles from TOVS sounder (or, alternatively, from meteorological analyses). Cloud information is deduced from the analysis of satellite visible and IR data, to discriminate between the cloud types (and associated optical properties, base, depth,...). Studies by *Darnell et al* (1983) (the first), *Gupta* (1989), *Frouin et al* (1988b), and *Schmetz et al* (1986) can be cited, among others.

The major problem is the retrieval of cloud parameters. *Frouin et al* (1988b) compare four methods, the most complex one relating cloud reflectance to optical depth, then deducing the liquid water content, from which the cloud emissivity can be inferred. The cloud base height is also deduced from the cloud top and liquid water content, using a statistical relationship. Note that Frouin's approach, as well as Schmetz' one, are only applicable at daytime, since they use visible channels to obtain cloud parameters. *Brisson et al* (1993) applied a bulk formula to meteorological model analyses, and included an automatic cloud classification, based on Meteosat visible / IR images, to get the cloud parameters (prescribed for each cloud type). *Schmetz et al* (1986) also used operational meteorological fields at 1000 and 850 hPa..

Tuzet (1990) adapted from *Brutsaert* (1975) a semi-empirical formulation, taking operational meteorological data for water vapour profiles. *Gupta* (1989) used a parameterization to calculate the DLF as a linear function of the fractional cloud cover, with cloud properties prescribed (3 layers), and TOVS water vapour profiles.

Statistical methods are based on regressions between satellite radiances and surface fluxes, the data used being either measurements, or results of detailed radiative transfer models, and are found to work rather well in clear sky (*Morcrette and Deschamps*, 1986).

2.3 Net surface fluxes

To obtain the net solar and longwave fluxes, the surface temperature, albedo and emissivity must be determined. The surface albedo is currently deduced from visible radiances, as shown in section 2.1. However, *Cess and Vulis* (1989) specifically examined its retrieval. They emphasized the effect of atmospheric conditions on the surface albedo, due to alterations of the solar beam as it passes through clouds and gases.

Computation of the upward part of the surface longwave flux requires the accurate knowledge of the surface temperature and the surface emissivity. Again, for the surface temperature, an atmospheric correction must be applied to satellite IR data to eliminate the atmospheric contribution (split-window technique, for example). The radiative temperature is representative of the uppermost few micrometers of the surface (or vegetation canopy). Over ocean, the atmospheric correction is the main limitation of the SST measurement accuracy (accuracy ≥ 0.5 K), but calibration is done in terms of bulk temperature instead of skin temperature (due to the routine data used), introducing errors reaching 0.5 K in some cases (*Schluessel et al,* 1987). Over land, the high variability of the soil properties and vegetation makes the significance of a surface temperature at the satellite pixel scale questionable when the soil is partially covered by vegetation. *Saunders* (1989) noted that the surface temperature is very difficult to validate due also to its rapid change occasioned by cloud passing. *Kustas et al* (1990) experimentally and theoretically studied the radiative transfer within the vegetation depth. They noted the importance of the viewing angle, due to shading effect of leaves.

The surface emissivity is still mostly unknown, as noted by *Darnell et al* (1992) : it is assumed to be close to unity over land (and therefore assigned to 1 in most surface longwave flux calculations). Studies aimed at its retrieval from satellites are under development : *Li and Becker* (1993) evaluated both the actual surface emissivity and the land surface temperature from AVHRR measurements, using spectral properties of the various channels.

When calculating the net radiation, the errors due to all the approximations in the upward and downward fluxes are added. An attractive method is to directly relate the net radiative surface flux to the top-of-the-atmosphere (TOA) fluxes. As it has been shown that the net radiation is dominated by solar flux variation (*Darnell et al*, 1992), some authors have attempted to directly relate the net flux to satellite data. *Pinker and Tarpley* (1988) related visible /IR counts from GOES/VISSR to surface measurements on selected sites using statistical relationships (Fig.3). The problem they noted is the little knowledge of space/time net radiation variation.

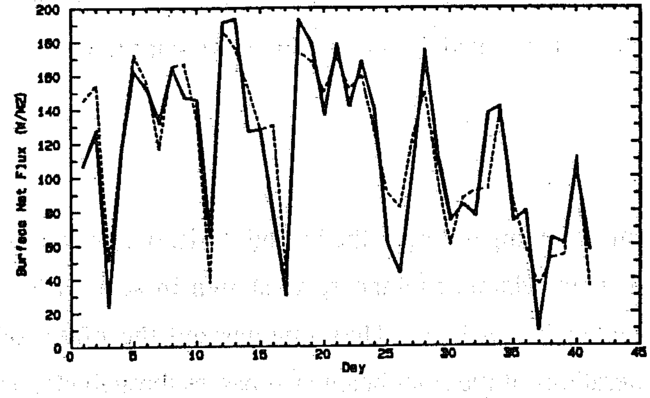
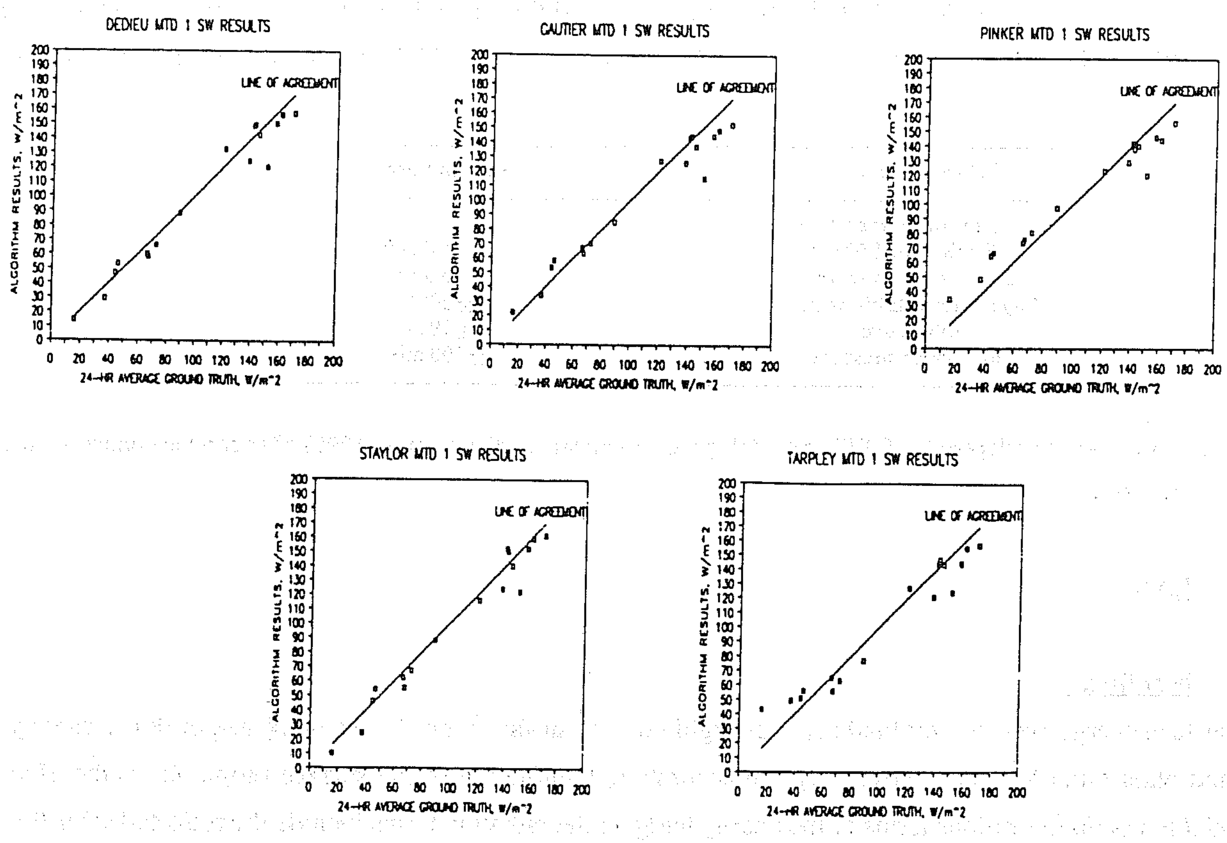


Fig. 3 : Daily averaged surface net radiation at a particular site, over 40 days. Solid line : measured net radiation; dashed line : predicted from the planetary net radiation using visible and IR GOES counts (from Pinker and Tarpley, 1988).

2.4 Validation of the retrieved fluxes

Validation studies are generally achieved by comparison of retrieved fluxes and local measurements. Sensitivity and error analysis is also determined by comparison between different methods (statistical versus modelling techniques, for example).

Whitlock et al (1990) made an intercomparison experiment of downward solar irradiance schemes, based on ISCCP Wisconsin experiment and SRB (Surface Radiation Budget experiment) data. Several physical and empirical methods were tested, and the main result of the comparison, shown in Fig. 4, was that simple methods (*Gautier, Dedieu, Pinker and Tarpley*) are as accurate than complex approaches (*Rossow*). They note that the monthly averaged flux may be obtainable to an accuracy of 10 Wm^{-2} (for a satellite calibration within 5%). *Frouin et al* (1988a) succesfully compared retrieved fluxes over the ocean with local data, reporting errors on the daily insolation of the order of 12 Wm^{-2}. *Schmetz* (1989) compared the accuracies reported in several papers for physical methods. All are of the order of 5% in monthly mean, but instantaneous retrievals are much more inaccurate (15 - 18 Wm^{-2}). Their weakness is the lack of input data (water vapour and aerosols, essentially) to drive the model. They have to be carefully tuned to both accurate surface measurements and accurate radiative transfer calculations. The water vapour input can be provided by operational weather analyses (*Brisson et al*, 1993), or by satellite profilers (in the future).



	CLEAR-SKY DAY W/m^2	OVERCAST DAY W/m^2	17-DAY AVG W/m^2	17-DAY RMS W/m^2	ALG/GT SLOPE
GT	+161	+16	+104		
(ALG-GT) DIFFERENCES:					
CHOU-MTD 2B	+13	+11	+7	+12	+1.05
DEDIEU-MTD 1	-5	-2	-4	+11	+0.95
GAUTIER:					
-MTD 1	-13	+6	-4	+12	+0.85
-MTD 2A	+1	-2	0	+11	+0.94
-MTD 2B	-1	-3	-5	+11	+1.00
PINKER:					
-MTD 1	-17	+18	+1	+14	+0.76
-MTD 2A	-12	+5	-5	+14	+0.83
-MTD 2B	-8	-1	-7	+11	+0.94
ROSSOW-MTD 2B	6	-5	5	+12	+1.01
STAYLOR:					
-MTD 1	-2	-6	-5	+10	+0.98
-MTD 2A	-2	-9	-5	+11	+0.97
-MTD 2A REV	-2	-6	-2	+11	+0.93
TARPLEY-MTD 1	-6	+27	-2	+13	+0.84

Fig.4 : Intercomparison of surface downward shortwave retrievals in daily average, compared with local measurements. The table gives the summary of discrepancies for each scheme (from Whitlock et al, 1991).

Concerning the longwave surface flux, the accuracy of physical retrievals is essentially related to the accuracy of the atmospheric profiles, in clear sky. TOVS temperature and mixing ratio profiles have errors reaching 2-3 K and about 30%, respectively, which may induce a 20-60 Wm^{-2} on the flux (*Frouin et al*, 1988b). *Morcrette and Deschamps* (1986) compared retrieved surface longwave flux from satellite measurements (HIRS sounder) using a statistical method, and a radiative transfer model (and radiosoundings as inputs), finding a standard error of 16 - 30 Wm^{-2} for satellites retrievals and less than 10 Wm^{-2} for the model with respect to ground measurements. *Bréon et al* (1991) compared two simple retrievals to a complete radiative transfer model, and found some systematic differences between them that they attributed to the prescribed cloud properties in each method.*Gupta et al* (1992) analyzed the errors in a DLF parameterization (*Gupta*, 1989), in comparison with full radiative transfer calculations. Both methods were found to be similarly accurate in clear sky and in cloudy conditions and the major source of error was found to be TOVS profiles, inducing errors of 17 - 23 Wm^{-2} on the DLF (15 - 20 Wm^{-2} on the net LF), as shown in Table 1.

TOVS parameter	Random error
Layer mean temperatures:	
Surface to 850 mb	±2·5 deg K
850 mb to tropopause	±2·25 deg K
Layer precipitable water	±30%
Cloud cover	±20%
Cloud-base pressure	±100 mb

Table 1: random errors adopted for TOVS meteorological parameters by Gupta et al (1992) after carefully analysing the TOVS data.

3. LAND

3.1 heat fluxes

The surface energy budget over land depends highly on the surface type (bare soil, sparse or dense canopy, soil and plant humidity, snow cover,...). An accurate determination of the surface properties is therefore essential to obtain the various terms of the energy budget : the radiation terms include the reflected solar flux (knowledge of the surface albedo) and the upward longwave flux (knowledge of the emissivity and the temperature) ; the heat fluxes are the latent and sensible heat fluxes, both depending on the surface temperature, and the heat flux in the soil, which depends on its nature and humidity content. The extreme horizontal variability of these parameters are the major problem of any retrieval method based on satellite data.

At the local scale, many models have been developed, mainly for agrometeorological purposes. They are constituted of parameterizations of the soil (one to several layers), a surface layer (including canopy) and a boundary layer scheme, with a description of exchanges between the different layers. The surface energy budget is therefore at the center of their formulation. Specific approaches for the retrieval of surface fluxes and the evapotranspiration of vegetation using satellite optical data are based on such models. They need however local data, both for the boundary layer (low level wind and temperature profile) and the soil (crop type, soil characteristics). Surface fluxes of heat and evaporation are generally written as a function of the gradient of temperature (partial pressure of water vapour for evaporation) with a resistance term depending on the surface / vegetation properties.

Models differ by the number of layers, the number of parameters determined from satellite, the inversion method, and the method used for getting the unknown parameters (semi-empirical determination, statistical regression on a particular data set,...). Studies by *Taconet et al* (1986), *Carlson* (1986), based on *Deardorff's* (1978) model (fig. 5) have demonstrated that the number of important parameters can be reduced in particular cases : over dense canopy, the global stomatal resistance (including the root zone humidity) is the key parameter, whereas the roughness and the available humidity (characterized by the thermal inertia and the diffusive conductance) are necessary over bare soil. Using visible / IR radiances near midday is sufficient for the model inversion over dense canopy, and two extreme temperatures are required for bare soil retrieval (the roughness being prescribed). More recent studies have extended these works to sparse vegetation cover (*Ben Mehrez et al*, 1992), and larger scales (*Serafini*, 1987, *Ottlé et al*, 1993). The use of a complete daily surface temperature cycle permit to retrieve several parameters, and thus to improve the flux determination (*Diak and Stewart*, 1989).

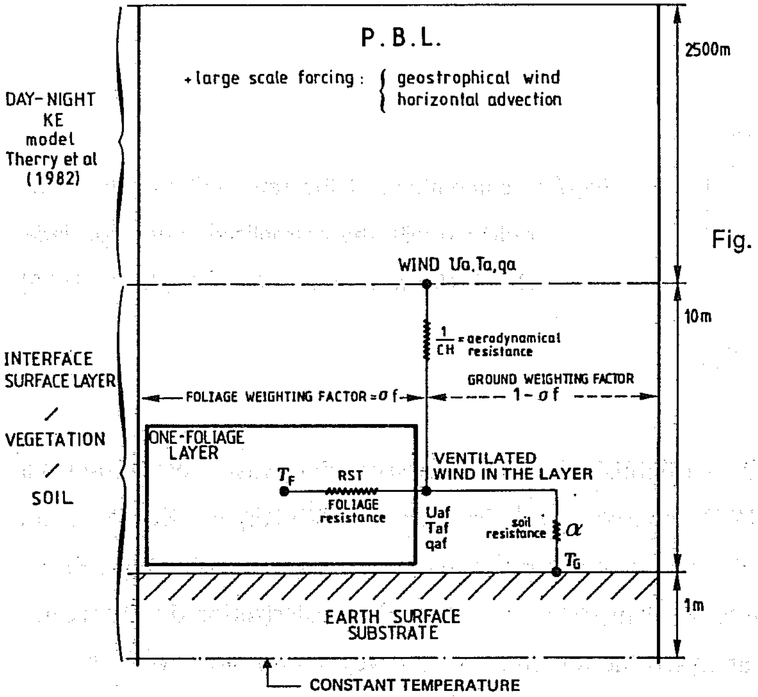


Fig. 5 : schematic representation of the surface - atmosphere interaction model of Taconet et al (1986).

Statistical formulations have also been proposed to use more directly satellite data radiances, or vegetation index (which are normalized combinations of visible and / or IR radiances), following the idea that satellite data, being non-local, are related to the energy budget at a larger scale than local measurements. Relations between radiances and vegetation index, as the NDVI (difference between NIR and Red reflectances, divided by their sum) are established with fluxes or relevant parameters.

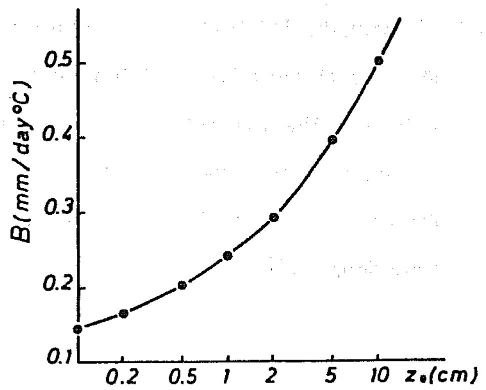


Fig.6 : variation of coefficient B with roughness for application to various sites (from Lagouarde, 1991).

Formulations linearly relating the sensible heat flux or the difference LE - Rn to the temperature gradient A + B (Ts - Ta) are currently used at a daily scale (*Lagouarde*, 1991, *Rosema and Fiselier*, 1990, for example), the slope (B) being a function of surface properties (fig. 6). Such a method is found to work at a regional scale, but it cannot be applied easily to another region, due to the necessary calibration of the A and B parameters. They also need additional data, from local measurements.

The previous methods work at a daily scale, neglecting the soil heat flux G. *Kustas and Daughtry* (1990) proposed to retrieve from satellite data the ratio of G on the net radiation, that they experimentally found to be nearly constant during a few hours around midday (Fig.7). They used a combination of radiances in the IR or visible (NDVI, NIR /visible).

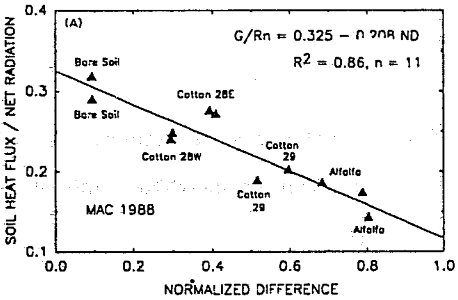


Fig.7 : comparison of the ratio soil heat flux / net radiation with the normalized vegetation index NDVI (from Kustas and Daughtry, 1990).

At a large scale, statistical relationships have been established between passive microwave measurements at 37 GHz and surface fluxes by *Choudhury*, 1991 and *Smith and Choudhury*, 1990 (Fig.8). However, the physical bases for these analyses are still lacking, even in the optical range, and studies are ongoing : *Prince and Choudhury* (1989) examined the statistical relationship between the 37 GHz polarization difference and the NDVI; *Wiegand and Richardson* (1990), analysed the relation between vegetation index with the LAI (leaf area index) and the evapotranspiration ; *Jackson and Schmugge* (1991), and *Jackson and O'Neill* (1991) studied the relative effect of the soil and vegetation in the microwave emission. They analysed the possibility of retrieving the surface humidity content and some vegetation parameters.

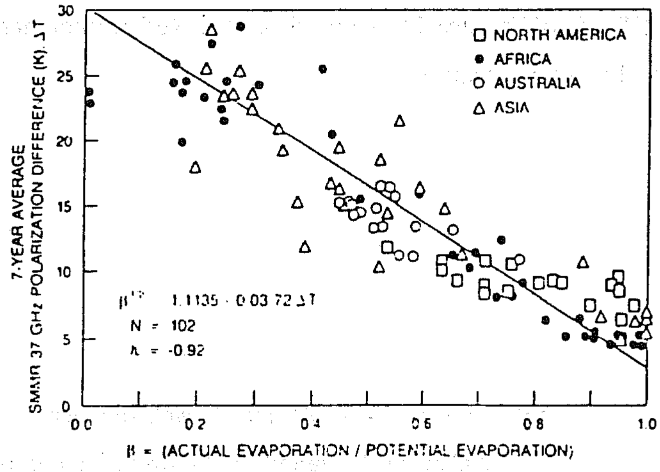


Fig. 8 : Relationship between annual average values of the polarization difference from SMMR 37 GHz data and the computed ratio of actual and potential evaporation (which is an indicator of the soil water availability to vegetation), after Choudhury, 1991.

3.2 Validation :

At the local scale, validation of the retrieved fluxes can be achieved using local data. Accuracies of the order of 10 - 20 % are obtained locally for the latent heat flux and the radiation. Using the FIFE campaign results, *Hall et al* (1991) tested retrievals of surface fluxes (simple parameterization of the turbulent fluxes). They noted that the sensible heat flux cannot yet been retrieved with a sufficient accuracy, due to the lack of knowledge on the canopy aerodynamical resistance, in particular. *Choudhury* (1991), also noted that an error of 1 K in the surface temperature could result in 10 - 50% error in the sensible heat flux. The retrieval of the latent heat flux should be less problematic, following *Hall et al* (1991), due to the high stomatal resistance compared with the aerodynamical resistance.

Diak and Stewart (1989) tested a retrieval method of both heat fluxes based on a interface model, applied using hourly measurements of the surface temperature (12 hour-run) and initialized over several sites using BL profiles and local informations. Validation consisted of comparing output profiles with new measurements, and the various sources of errors were investigated, resulting in a global accuracy of about 10% on the sensible heat flux. The modelling approach thus seems more accurate than the empirical / statistical approach. However, the main problem of retrieval method based on models is their limits of applicability : clear atmosphere, no advection, no precipitation event during the model run in particular.

4. OCEAN

4.1 surface heat fluxes

Over oceans (in places free of ice), net radiative fluxes can be obtained more easily than over ground, because the surface albedo is nearly constant, and the surface is homogeneous over a larger scale. The variation of surface emissivity (angular and spectral variations) with sea state however, is weakly known. Concerning the downward irradiances, however, problems are similar or even greater, due to the relative weakness of maritime cloud knowledge. The specificity of the ocean surface is that the net energy budget is not balanced at a daily scale, contrary to land surface: the residual term is the heat flux entering the ocean, which is of a great importance for ocean heat budget analysis. This term cannot be directly measured, and is deduced from the net energy equation. It is therefore essential to determine the surface radiative and heat fluxes with a very good accuracy.

Compared with the variety of methods developed over land surface, the published work about the retrieval of ocean surface heat fluxes is very poor. In particular, no attempt has been reported to directly retrieve the sensible heat flux, which is about a tenth of the latent heat flux (Bowen ratio ≈ 0.11). An indirect determination from the latent heat flux retrieval has been tested by *Michael and Nunez* (1991), using a parameterization of the Bowen ratio as a function of the surface temperature, following *Priestley and Taylor* (1972).

The first attempt to infer the latent heat flux was made by *Liu* (1984), using a simple bulk parameterization applied to SMMR data : this microwave radiometer provided the surface temperature (SST), surface wind speed (Vs) and the columnar water vapour amount (W). From the last parameter, *Liu and Niiler* deduced the near surface specific humidity qa using a statistical relationship established from a series of island radiosounding . Applying this to SMMR data, they infered the LE in monthly mean over boxes of 2°x2°, with an estimated error of about 30 Wm^{-2} (or 30%). *Liu* (1986) and *Liu et al* (1991) tested it in tropical latitudes, then extended the qa - W relationship to other latitudes and shorter scales (Fig. 9).

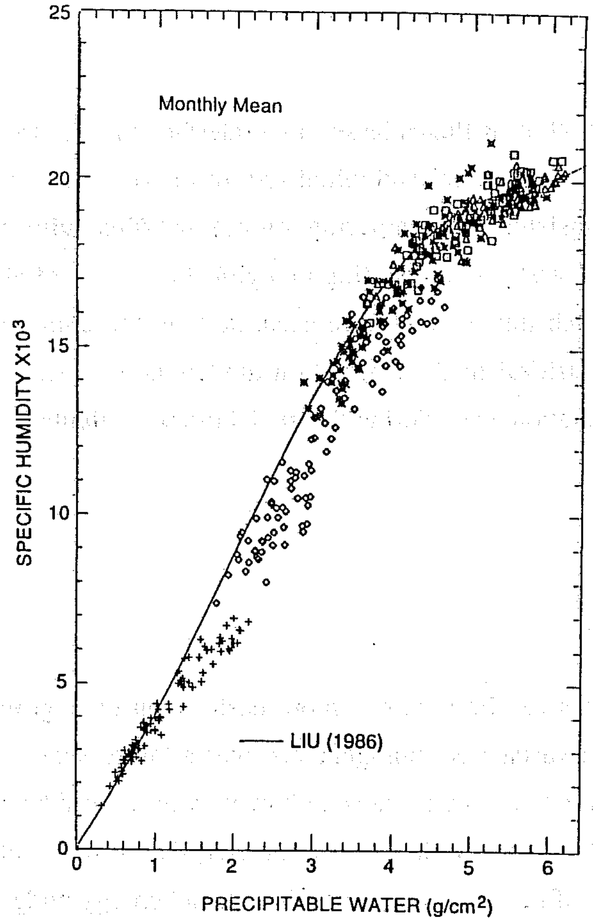


Fig.9 : Scatterplot of monthly averaged integrated water vapour content versus low level specific humidity, from 5 island radiosounding over 9 years. The line represents the polynomial relationship established by Liu (1986). From Liu et al (1991).

The validity of this qa - W relationship is questionable : *Liu* (1986) noted that the relationship fails in high-latitude northern oceans during summer, even in monthly mean, and *Liu et al* (1992) found a monthly mean error of 1.15 gkg^{-1} for qa on the global ocean (using ECMWF analyzed humidity profiles); *Esbensen et al* (1993), using SSM/I data, clearly demonstrated that it is mainly responsible for the observed discrepancies (errors of 2 gkg-1 are systematically found in the tropics, as well as in the middle and high latitudes). Surprisingly, *Hsu and Blanchard* (1989) found Liu's relationship valuable at small scales, by comparison with individual RS profiles.

The *Esbensen et al* (1993) demonstration should now clarify the situation : this approach is not relevant for short scales, due to the extreme variability of the vertical distribution of humidity. It is no longer useful for climate studies, because a 30 Wm^{-2} error in monthly mean is much more higher than acceptable (less than 10 Wm^{-2}). First comparisons of SSMI retrieved evaporation with COADS estimate show errors over the summertime high-latitude regions of both hemispheres (downward flux), and during August in the eastern equatorial Pacific (Fig. 10). The simplicity of this LE retrieval, however, made it attractive to several authors. Following a similar approach, *Miller and Katsaros* (1992) slightly modified the relationship to derive qs-qa from W using additional SST measurements, and *Michael and Nunez* (1991) attempted to retrieve the net energy budget over the ocean, calculating the latent heat flux using a statistical relationship qs-qa as a linear function of W (from TOVS), after showing at the local site that Liu's polynomial expression fails. They reported for the total heat flux an error of about 45 Wm^{-2} over a long duration.

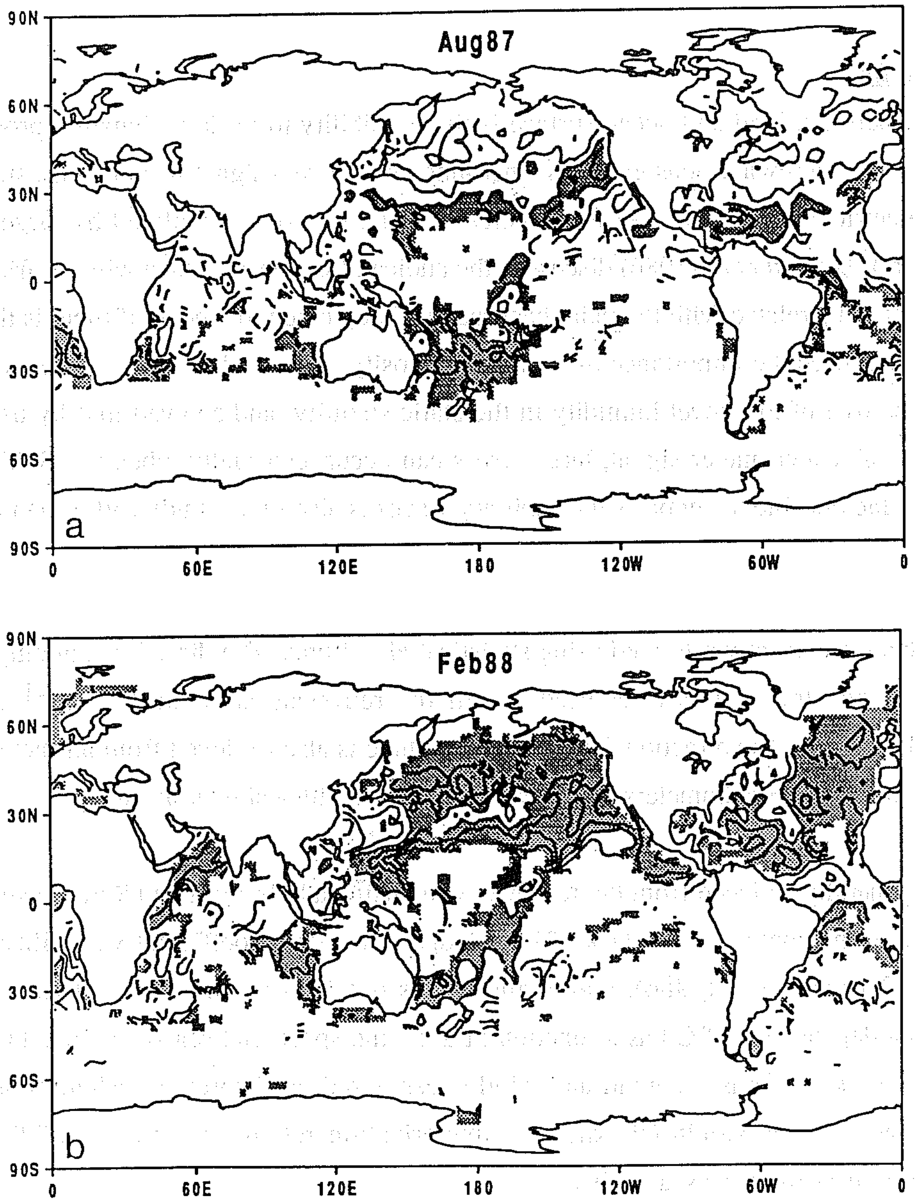


Fig. 10 : Evaporation obtained by applying Liu's method to SSM/I data minus evaporation calculated from COADS data. Contour interval is 10^{-5} $kgm^{-2}s^{-1}$. Dark and light shaded areas correspond to positive and negative differences, respectively. From Esbensen et al (1993.)

An alternate approach has been proposed by *Gaspar et al* (1990) and *Roquet et al* (1993): using a ocean surface layer model, the surface flux budget can be controled through inversion on the surface temperature, the downward radiation and friction velocity being given as inputs (independently retrieved from satellite measurements). Note that the partition between the components of this term into sensible and latent heat flux requires additional information. This method is rather close to the modelling methods used for land surface heat budget retrieval. The main difference is that the ocean surface layer is dominated by dynamic processes. In these first tests, non-advective situation were chosen, permitting to retrieve the surface flux part using a 1-D model. For application in the open ocean, a three-dimensional model is necessary, including the ocean circulation (under development at the French Met. Office).

4.2 Momentum flux

Another difference between land and ocean surface is the possibility to retrieve dynamic properties of the ocean from spaceborne microwave sensors. These instruments receive a signal from the sea surface, which depends on its dielectric and roughness characteristics (capillary waves, modulated by larger waves, and foam for radiometers). *Pierson et al* (1986) discussed the choice of the near surface wind or friction velocity as the best parameter to be related with the radar backscatter. They noted that none of them is the best single parameter, and they showed the importance of seawater viscosity on the radar signal. *Gernaert and Larsen* (1993) examined the role of low level humidity in the static stability, and showed that by using a neutral stability in analysis of scatterometer signal, large errors can occur, especially when the SST is high. The importance of other factors able to suppress the capillary waves is also under study (oil or natural slicks, for example).

The near surface wind is currently retrieved using statistical algorithms. The direction can only be obtained with scatterometers, and the accuracy reported for all the retrievals is about ± 2 ms^{-1} for the wind magnitude, and ± 10 - 20° for the direction. The wind magnitude is also retrieved from altimeter data (along the track) and from microwave radiometers as SMMR and SSM/I, with a similar accuracy.

The wind stress is generally deduced from the retrieved wind using a bulk formula (*Busalacchi et al*, 1993). The main weakness of this method is the lack of knowledge of the drag coefficient variability : *Large and Pond* (1981), and *Gernaert et al* (1986), comparing fluxes obtained by direct correlation and by bulk formulation, found a dependence of Cd as a function of the wind speed and sea state (Fig. 11). *Wu* (1992) recently proposed new algorithms for wind and wind stress based on theoretical calculations (equations describing the surface, and a Monin-Obukhov parameterization relating u and u*) of the near-nadir microwave specular returns from the sea surface.

Comparison studies have been performed to validate the near surface wind. Most of the comparisons were conducted using local data from ship reports and buoys (*Goodberlet et al*, 1989 for the SSM/I, for example). Comparison with meteorological analyses was found to be as accurate and easier: *Stoffelen and Anderson*

(1992) thus validated the ERS-1 scatterometer data, and *Eymard et al* (1993) revealed large errors in the SMMR surface wind.

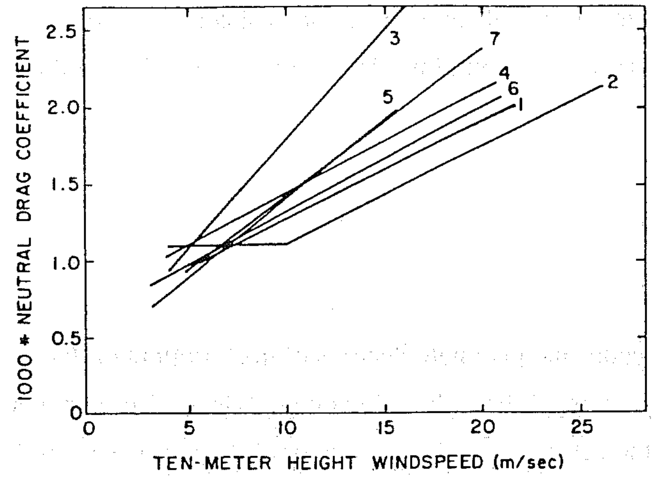


Fig. 11 : Compilation of published drag coefficient as functions of the near surface wind speed (regression equations), from Gernaert et al, 1986.

4.3 Sea ice

The sea ice energy budget is a complex ocean - atmosphere interaction problem : sea ice formation prevents the ocean from ventilating heat to the atmosphere, but highly reflective ice causes reduction of solar energy to the ocean. Thus the key parameters are the ice distribution at all scales, the cloudiness, and the surface wind. Most of the satellite studies in polar areas have concerned the ice distribution and characteristics (age, surface state), using visible and microwave radiometers, and recently using SAR data (from ERS-1 mainly). To obtain the sea ice energy budget, information from the ice bottom is necessary (formation, melting), and ocean dynamical processes are needed (advection, convection). Complex models have been developed, but satellite informations have rarely been utilized. *Thomas and Rothrock* (1989) have attempted to introduce SMMR estimates of ice concentration in a sea ice model. Using additional informations from buoys and ice motion through a numerical analysis procedure, they deduced ice properties from the satellite data (age, surface characteristics).

The ice concentration retrieval, itself, is still investigated, by comparison between microwave and optical sensors (*Emery et al,* 1991, *Steffen and Schweiger,* 1991). Considering the Landsat imagery as a reference, the problem was to correctly calibrate microwave data which have a poorer resolution, but for which clouds are transparency.

A major problem is indeed the arctic clouds : they form a quasi-permanent cover over the polar regions, and their radiative properties are difficult to determine, due to the similar radiances of ice surface and ice clouds. However, as noted by *Curry and Ebert* (1992), accurate determination of surface radiation fluxes is of particular importance, due to the sensitivity of sea ice thickness to the surface radiation budget and the possible importance of polar cloud cover in the ice-albedo climate feedback mechanism. Recent modelling experiments conducted by *Royer et al* (1990) suggested that the stability of the heat budget of an ice - free Arctic ocean may depend critically on the reaction of the local cloud cover. They determined the annual cloud optical properties necessary to reproduce both the outgoing fluxes at TOA, (from ERBE data) and the available determinations of surface fluxes, using a 1-D model. *Schweiger and Key* (1992) analysed the quality of the monthly cloud cover from ISCCP data, and found systematic errors (summer clouds underestimated by satellites by 5 - 35% with respect to surface observations, due probably to algorithms), and large uncertainty in winter (maybe due to ice crystal precipitation) They pointed out the need of a comprehensive validation program for the Arctic.

5 COMPARISON WITH MODELS

GCM and NWP generally include a radiative transfer code, and parameterizations of the turbulent exchanges at the surface. The quality of these schemes is mostly assessed through indirect comparisons. For example, *Miller et al* (1993) evaluated the effect of changing the parameterization of evaporation over oceans in the ECMWF model by analysing the atmospheric tropical circulation and rainfall patterns. *Alves* (1991, 1992) analysed the surface flux parameterization in two models of the British Met. Office through the forcing of an ocean circulation model.

There is thus a need for validation data at regional to large scales. Satellites, due to their large or global coverage, can indeed help in such validation. Moreover, there have been a great effort since about 15 years for improving retrieval methods of surface fluxes from satellite data.

In the previous sections, we noticed that very few of them work without additional information from local and meteorological sources (input for models, or local calibration):

- In the case of radiative fluxes, the main problems are the determinations of low level atmosphere and cloud structure, because satellite profilers are far from providing boundary layer profiles, and cloud base cannot be remotely sensed from space. Another difficulty is the correct mapping of surface characteristics at various scales (albedo, emissivity and temperature), the occurence of clouds often masking the surface in many places (e.g. polar ice).
- Land surface heat flux retrieval methods all need some knowledge about the low atmosphere (temperature, wind). Some characteristics of the surface (roughness, occurence of rain,...) are prescribed from local information, or rather arbitrarily at a larger scale.
- Ocean surface heat fluxes are not still correctly retrieved from space. As studies are aimed at a large scale retrieval (for ocean heat budget), the weakness of local measurements make them useless. The determination of momentum fluxes is much more promising, although bulk formulae still need to be assessed for all weathers (drag coefficient variability).

Despite the above-mentioned limitations, some of the techniques for retrieving radiative fluxes are operationally used (*Schmetz et al*,1986, *Brisson et al*, 1993) for regional applications. At a global scale, the retrieved surface radiation (*Darnell et al*, 1992, *Chertock et al*, 1992) derived from ERB or ISCCP cloud data set appear as a useful tool for testing GCM.

The difficulty to apply easily these methods to any location or time, and their insufficient accuracy, however, prevents one to use most of them for model validation : *Morcrette and Deschamps* (1986) show that the pure satellite retrieval does not lead to a better accuracy than using ECMWF analysed fields. An alternate approach consists of using more directly the relevant satellite data, as also concluded *Isaacs et al* (1986).

For example, *Cess et al* (1993) compared the TOA - surface shortwave irradiance relationship obtained with the ECMWF model with the one obtained using local and ERBE data to verify the behaviour of the model radiation code; *Buriez et al* (1988) examined the sensivity of the regional radiation budget over the eastern Atlantic to cloud cover in the ECMWF model, by comparison with accurate cloud files (NEPHOS data set); *Saunders* (1989) examined the relevance of AVHRR data (SST, cloud cover, cloud top temperature) for mesoscale NWP, detecting some errors in the model fields. They noted the potential usefulness of skin temperature measurement, as input in the model radiative transfer scheme. *Li and Le Treut* (1989) tested a prognostic cloud scheme in a GCM, by computing optical properties of the simulated clouds, then comparing them to ISCCP data..

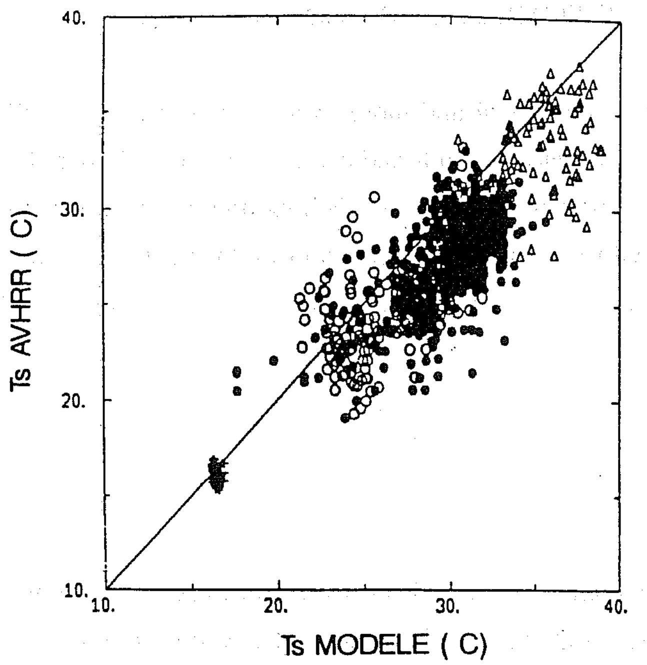


Fig. 12 : Correlation between the observed and predicted surface temperature for one AVHRR image over the HAPEX / MOBILHY domain in cloud free pixels. The different surface types are indicated by symbols (cross, triangle, black circles and white circles for, respectively sea, bare soil, fields and forest). From Noilhan et al (1991).

Over land, NWP and GCM include a surface parameterization (*Noilhan et al*, 1989, *Blondin*, 1988, *Wetzel and Chang*, 1988), which is necessarily much more simple than surface models developed for local agrometeorological purposes. Some experiments have been designed to offer the possibility of comparing regional atmospheric models and satellite methods to local measurements. The HAPEX/MOBILHY experiment has permitted such comparisons : *Mascart et al* (1991) and *Mahfouf* (1991) used local data for adjusting some parameters of the surface flux parameterization in mesoscale models; *Noilhan et al* (1991) also adjusted the surface parameterization in a 3-D model (roughness, stomatal resistance, LAI, vegetation fraction) using local data at selected sites, then tested the model by comparison of the predicted cloud cover and surface temperature with AVHRR data (Fig. 12).

Over ocean, comparisons mainly concern the momentum flux (or equivalently the surface wind) : *Busalacchi et al* (1993) tested the quality of the momentum flux derived from two models, three wind data bases and SSM/I in monthly mean, with the purpose of selecting the best source for ocean model forcing ; *Lee and Boyle* (1991) compared SSM/I wind with outputs of an operational mesoscale model. They pointed out the advantage of such a fine description of the surface wind for mesoscale modelling. *Anderson et al* (1991), after carefully analysing the SEASAT scatterometer wind, compared it to the ECMWF standard analysis, with an assimilation. objective A different approach was tested by *Guillaume and Mognard* (1992), who evaluated the quality of the surface wind produced by a mesoscale model over sea by forcing a wave model and comparing both the wind and significant wave height to GEOSAT altimeter data. Concerning the latent heat flux, the discussion in section 4.1 has shown that Liu's method is mostly inadequate. The columnar water vapour content, however, may be used in the test of the evaporation parameterization since *Miller et al* (1992) showed the great impact of a minor change in the evaporation to the tropical circulation and precipitation. For example, *Eymard et al* (1993) found systematic errors in the ECMWF model humidity field in particular areas of the ocean basins, compared with SMMR and SSM/I data, respectively.

Thus, the increasing availability of satellite data, from operational and more experimental satellites, will allow to develop comparison methods, adapted to the test of various fields and parameterizations. In parallel, other studies will continue to improve the independent retrieval methods. This is important as well, because these techniques are based on careful comparisons with local measurements and often include complex surface models, and therefore could in the future benefit to atmosphere numerical models (improved parameterizations, new data assimilation).

6 CONCLUSION

Considering the capability of satellite sensors to provide atmosphere and surface parameters, many studies have been conducted to retrieve some terms of the surface - atmosphere interaction. The visible and infrared spectrum has been mainly used to determine surface optical and thermal properties (albedo, emissivity and temperature) and clouds characteristics (cloud cover, top temperature). The sounders provide some indications on the temperature and humidity vertical distribution, which can be combined with the previous to estimate surface fluxes (radiation budget terms) through modelling or empirical methods. On land surface, optical sensors are used mostly to determine the surface temperature, and research is ongoing on the retrieval of other soil and vegetation parameters (humidity content, in particular) from microwave measurements, which could help in extending the present methods to more complex cases (sparse vegetation cover) and larger scales. Over ocean, microwave active and passive instruments provide the surface wind, permitting to estimate the momentum flux. The heat flux retrieval has been still limited, due to the lack of information about the low-level atmosphere thermal content.

Developments may be expected for the longwave radiative flux, with the new profilers AMSU A/B, and for the land surface heat budget, with the use of microwave measurements. Over ocean, may-be the development of inverse methods based on ocean surface layer modelling will change the present situation.

The main interest of these methods for numerical modelling is the better use of satellite data they introduce. Moreover, in some cases, it may be useful to directly compare GCM or NWP surface flux outputs to results of independent methods (detailed experiments, in particular, or seasonal variations). Finally, some of the algorithms (empirical formulae or parameterizations) developed in these satellite retrieval techniques might be used in numerical models.

References :

Alves, J.O.S., 1991 : An assessment of the surface fluxes from the Meteorological Office numerical weather prediction models. Part I: Momentum. Meteorol. Magazine, 120, 200 - 211.

Alves, J.O.S., 1992 : An assessment of the surface fluxes from the Meteorological Office numerical weather prediction models. Part II: Heat and Fresh water. Meteorol. Magazine, 121, 59 - 83.

Anderson, D., A. Hollingsworth, S. Uppala, and P. Woyceshyn, 1991 : A study of the use of scatterometer data in the ECMWF operational analysis-forecast model. 1. Quality assurance and validation. J.Geophys. Res., 96, C2, 2619 - 2634.

Ben Mehrez, M. O. Taconet, D. Vidal-Madjar and Y. Sucksdorff, 1992 : calibration of a flux model over bare soils during HAPEX-MOBILHY experiment. Agric. For. Meteor., 58, 257 - 283.

Bishop, J.K. and W.B. Rossow, 1991 : Spatial and temporal variability of global surface solar irradiance. J.Geophys. Res., 96, C9, 16839 - 16858.

Blondin, C., 1988 : Research on land surface parameterization schemes at ECMWF. Parameterization of fluxes over land surface, ECMWF, 285 - 330.

Bréon, F.M., R. Frouin and C. Gautier, 1991 : Downwelling longwave irradiance at the ocean surface : an assessment of in-situ measurements and parameterizations. J.Appl. Meteor., 30, 17 - 31.

Brisson, A., P. Le Borgne, A. Marsoin and T. Moreau, 1993 : surface irradiances calculated from Meteosat sensor data during SOFIA/ASTEX. Accepted in Int. J. Rem. Sens..

Brutsaert, W., 1975 : On a derivable formula for longwave radiation from clear skies. Water Resources Research, 11, 742 - 744.

Buriez, J.C., B. Bonnet, Y. Fouquart, J.F. Géleyn and J.J. Morcrette, 1988 : Comparison of model-generated and satellite-derived cloud cover and radiation budget.J.Geophys. Res., D, 93, 3705 - 3719.

Busalacchi, A.J., R.M. Atlas, and E.C. Hackert, 1993 : Comparison of Special Sensor Microwave Imager vector wind stress with model-derived and subjective products for the tropical Pacific. J.Geophys. Res., 98, C4, 6961 - 6977.

Carlson,T.N., 1986 : Regional scale estimates of surface moisture availability and thermal inertia. Remote Sensing Review, 1, 197 - 247.

Cess, R.D. and I.L. Vulis, 1989 : Inferring surface solar absorption from broadband satellite measurements. J. Climate, 2, 974 - 985.

Cess, R.D., S. Nemesure, E.G. Dutton, J.J. DeLuisi, G.L. Potter and J.J. Morcrette, 1993 : The impact of clouds on the shortwave radiation budget of the surface - atmosphere system : interfacing measurements and models. J. Climate, 6, 308 - 316.

Chertock, B., R. Frouin and C. Gautier, 1992 : A technique for global monitoring of net solar irradiance at the ocean surface. Part II : validation. J.Appl. Meteor., 31, 1067 - 1083.

Choudhury, B.J., 1991 : Multispectral satellite data in the context of land surface heat balance. Reviews of Geophysics, 29, 217 - 236.

Curry, J.A., and E.E. Ebert, 1992 : Annual cycle of radiation fluxes over the arctic ocean : sensitivity to cloud properties. J. Climate, 5, 1267 - 1280.

Darnell, W.L., S.K. Gupta and W.F. Staylor, 1983 : Downward longwave radiation at the surface from satellite measurements. J. Climate Appl. Meteor., 22, 1956 - 1960.

Darnell, W.L., W.F. Staylor, S.K. Gupta and F.M. Denn, 1988 : Estimation of Surface insolation using sun-synchronous satellite data. J. Climate, 1, 820 - 835.

Darnell, W.L., W.F. Staylor, S.K. Gupta, N.A. Ritchey, and A.C. Wilber, 1992 : Seasonal variation of surface radiation budget derived from International Satellite Cloud Climatology project C1 data. J.Geophys. Res., 97, D14, 15741 - 15760.

Deardorff, J.W., 1978 : Efficient prediction of ground surface temperature and moisture, with inclusion of layer of vegetation. J.Geophys. Res., 83, C4, 1889 - 1903.

Diak, G.R., and T.R. Stewart, 1989 : Assessment of surface turbulent fluxes using geostationary satellite surface skin temperatures and a mixed layer planetary boundary layer scheme. J.Geophys. Res., 94, D5, 6357 - 6373.

Emery, W.J., M. Radebaugh, C.W. Fowler, D. Cavalieri and K. Steffen, 1991 : A comparison of sea ice parameters computed from advanced very high resolution radiometer and Landsat satellite imagery and from airborne passive microwave radiometry. J.Geophys. Res., 96, C12, 22075 - 22085.

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, C4, 7081 - 7101.

Eymard, L., R. Bernard and J.Y. Lojou, 1993 : Validation of microwave radiometer geophysical parameters using meteorological model analyses. Int. J. Rem. Sens., 14, 1945 - 1963.

Frouin, R., and B. Chertock, 1992 : A technique for global monitoring of net solar irradiance at the ocean surface. Part I : model. J.Appl. Meteor., 31, 1056 - 1066.

Frouin, R., C. Gautier, K.B. Katsaros, and R.J. Lind, 1988a : A comparison of satellite and empirical formula techniques for estimating insolation over the oceans. J.Appl. Meteor., 27, 1016 - 1023.

Frouin, R., C. Gautier and J.J. Morcrette, 1988b : Downward longwave irradiance at the ocean surface from satellite data : methodology and in-situ validation. J.Geophys. Res., C,93, 597 - 619.

Gaspar P., J.C. André and J.M. Lefevre, 1990 : The determination of latent and sensible heat fluxes at the sea surface viewed as an inverse problem. J.G.R., C, 95, 16 169 - 16 178.

Gautier, C., G. Diak, and S. Masse, 1980 : A simple physical model to estimate incident solar radiation at the surface from GOES satellite data. J.Appl. Meteor., 19, 1005 - 1012.

Gernaert, G, and S. Larsen, 1993 : On the role of humidity in estimating marine surface layer stratification and scatterometer cross-section. J.Geophys. Res., 98, C1, 927 - 932.

Gernaert, G.L., K.B. Katsaros, and K. Richter, 1986 : Variation of the drag coefficient and its dependence on sea state. J.Geophys. Res., 91, C6, 7667 - 7679.

Goodberlet, M.A., C.T. Swift, and J.C. Wilkerson, 1989 : Remote sensing of ocean surface winds with the SSM/I. J.Geophys. Res., 94, C10, 14547 - 14555.

Guillaume, A., J.M. Lefèvre, and N.M. Mognard, 1992 : The use of altimeter data to study wind and wave variability in the western mediterranean sea and validate fine mesh meteorological models. Oceanologica Acta, 15, 555 - 561.

Gupta, S.K., 1989 : A parameterization for longwave surface radiation from sun-synchronous satellite data. J Climate, 2, 305 - 320.

Gupta, S.K., A.C. Wilber, W.L. Darnell, and J.T. Suttles, 1992 : Longwave surface radiation over the globe from satellite data : an error analysis. Int. J. Rem. Sens., 14, 95 - 114.

Hall, F.G., P.J. Sellers, D.E. Strebel, E.T. Kanemasu, R.D. Kelly, B.L. Blad, B.J. Markham, J.R. Wang and F. Huemmrich, 1991 : Satellite remote sensing of surface energy and mass balance : results from FIFE. Remote Sens. Environ., 35, 187 - 199.

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, 14 530 - 14 545.

Isaacs, R.G., R.N. Hoffman, and L.D. Kaplan, 1986 : Satellite remote sensing of meteorological parametersq for global numerical weather prediction. Reviews Geoph., 24, 701 - 743.

Jackson, T.J., and P.E. O'Neill, 1991 : Microwave emission and crop residues. Remote Sens. Environ., 36, 129 - 136.

Jackson, T.J., and T.J. Schmugge, 1991 : Vegetation effects on the microwave emission of soils. Remote Sens. Environ., 36, 203 - 212.

Kustas, W.P., and C.S.T. Daughtry, 1990 : Estimation of the soil heat flux / net radiation ratio from spectral data. Agric. Forest Meteor., 49, 205 - 224.

Kustas, W.P., B.J. Choudhury, Y. Inoue, P.J. Pinter, M.S. Moran, R.D. Jackson and R.J. Reginato, 1990 : Ground and aircraft infrared observations over a partially-vegetated area. Int. J. Rem. Sens., 11, 409 - 428.

Lagouarde, J.P., 1991 : Use of NOAA AVHRR data combined with an agrometeorological model for evaporation mapping. Int. J. Rem. Sens., 12, 1853 - 1864.

Large, W.G., and S. Pond, 1981 : Open ocean momentum flux measurements in moderate to strong winds. J. Phys. Oceanogr., 11, 324 - 336.

Lee, T.F., and J.S. Boyle, 1991 : A synoptic comparison of SSM/I winds with output from an operational forecast system. Weather and forecasting, 6, 404 - 410.

Le Borgne, P., and A. Marsouin, 1988 : Détermination du flux ondes courtes incident à la surface. Mise au point d'une méthods opérationnelle à partir des données du canal visible de Meteosat. La Météorologie, 20, 9 - 19.

Li, Z, H.G. Leighton, K. Masuda and T. Takashima, 1993 : Estimation of SW flux absorbed at the surface from TOA reflected flux. J. Climate, 6, 317 - 330.

Li, Z.X., and H. Le Treut, 1989 : Comparison of GCM results with data from operational meteorological satellites. Ocean-Air Inter., 1, 221 - 237.

Li, Z.L., and F. Becker, 1993 : Feasibility of land surface temperature and emissivity determination from AVHRR data. Remote Sens. Environ., 43, 67 - 85.

Liu, W.T., 1984 : Estimation of latent heat flux with SEASAT-SMMR: a case study in North Atlantic. "Large scale Oceanographis Experiments and satellites", compilation by C. Gautier and M. Fieux. (Reidel), 205 - 221.

Liu, W.T., W. Tang and P.P. Niiler, 1991 : humidity profiles over the ocean. J. Climate, 4, 1023-1034.

Liu, W.T., W. Tang, and F.J. Wentz, 1992 : Precipitable water and surface humidity over global oceans dfrom SSM/I and ECMWF. J.Geophys. Res., 97, C2, 2251 - 2264.

Mahfouf, J.F., 1991 : Analysis of soil moisture from near-surface parameters : a feasibility study. J.Appl. Meteor., 30, 1534 - 1547.

Mascart, P., O. Taconet, J.P. Pinty, and M. Ben Mehrez, 1991 : Canopy resistance formulation and its effect in mesoscale models : a HAPEX perspective. Agricul. Forest Meteor., 54, 319 - 351.

Michael, K.JH., and M. Nunez, 1991 : Derivation of ocean-atmosphere heat fluxes in a tropical environment using satellite and surface data. Internat. J. climatology, 11, 559 - 575.

Miller, D.K. and K.B. Katsaros, 1992 : Satellite-derived surface latent heat fluxes in a rapidly intensifying marine cyclone. Monthly Weather Review, 120, 1093 - 1107.

Miller, M.J., A.C.M. Beljaars, and T.N. Palmer, 1992 : The sensitivity of the ECMWF model to the parameterization of evaporation from the tropical oceans. J. Climate, 5, 418 - 434.

Morcrette, J.J., and P.Y. Deschamps, 1986 : Downward longwave radiation at the surface in clear sky atmospheres : comparison of measured, satellite-derived and calculated fluxes. Proc. ISLSCP Conf. Rome, ESA SP^{-2}48, 257 - 261.

Noilhan, J., J.P. Jullien, P. Lacarrère, T. Phulpin, and M. Stoll, 1991 : Quelques exemples d'utilisation des données satellitaires pour la modélisation atmosphérique à moyenne échelle. Proc. 5th Intern. Colloquium - Physical Measurements and signatures in Remote Sensing, Courchevel, france, 14 - 18 January 1991. Doc. ESA SP-319, 541 - 546.

Ottlé, C., and D. Vidal-Madjar, 1993 : Assimilation of soil humidity inversed from infrared remote sensing in an hydrological model over the HAPEX-MOBILHY region. Submitted to Int. J. Rem. Sens..

Pierson, W.J., W.B. Sylvester, and M.A. Donelan, 1986 : Aspects of the determination of winds by means of scatterometry and of the utilization of vector wind data for meteorological forecasts. J.Geophys. Res., 91, C2, 2263 - 2272.

Pinker, R.T. and J.D. Tarpley, 1988 : The relationship between the planetary and surface net radiation : an update. J. A. M., 27, 957 - 964.

Priestley, C.H.B., and R.J. Taylor, 1972 : On the assessment of surface heat flux and evaporation using large-scale parameters. MMonthly Wea. Rev., 100, 81 - 92.

Prince, S.D., and B.J. Choudhury, 1989 : Interpretation of Nimbus-7 37 GHz microwave brightness temperature data in semi-arid southern Africa. Int. J. Rem. Sens., 10, 1643 - 1661.

Ramanathan, V., 1986 : Scientific use of surface radiation budget data for climate studies. In Surface Radiation Budget for Climate Applications. NASA raference publ. 1169, 132pp.

Roquet, H., S. Planton, and P. Gaspar, 1993 : Determination of ocean surface heat fluxes by a variational method. J.Geophys. Res., 98, C6, 10211 - 10221.

Rosema, A., and J.L. Fiselier, 1990 : Meteosat-based evapotranspiration and thermal mapping for monitoring transgression in the Lake Chad region and Niger delta. Int. J. Rem. Sens., 11, 741 - 752.

Royer, J.R., S. Planton, and M. Deque, 1990 : A sensitivity experiment for the removal of the Arctic sea ice with the French spectral general circulation model. Clim. Dyn., 5, 1 - 17.

Saunders, R.W., 1989 : A comparison of satellite-retrieved parameters with mesoscale model analyses. Q. J. R. Meteorol. Soc., 115, 651 - 672.

Schluessel, P., H.Y. Shin, W.J. Emery, and H. Grassl, 1987 : Comparison of satellite-derived sea surface temperatures with in-situ skin measurements. J.Geophys. Res., 92, C3, 2859 - 2874.

Schmetz, J., 1989 : Towards a surface radiation climatology : retrieval of downward irradiances from satellites. Atmos. Res., 23, 287 - 321.

Schmetz, P., J. Schmetz and E. Raschke, 1986 : Estimation of the longwave radiation at the surface from satellite and grid point data. Theor. Appl. Climatol., 37, 136 - 149.

Schweiger, A.J., and J.R. Key, 1992 : Arctic cloudiness : Comparison of ISCCP-C2 and Nimbus-7 satellite-derived cloud products with a surface-based cloud climatology. J. Climate, 5, 1514 - 1527.

Serafini, Y.V., 1987 : Estimation of the evapotranspiration using surface and satellite data. Int. J. Rem. Sens., 8, 1547 - 1562.

Smith, R.C.G., and B.J. Choudhury, 1990 : relationship of multispectral satellite data to land surface evaporation from the Australian continent. Int. J. Rem. Sens. 12, 2069 - 2088.

Steffen, K., and A. Schweiger, 1991 : NASA team algorithm for sea ice concentration retrieval from DMSP SSMI: comparison with Landsat satellite imagery. J.Geophys. Res., 96, C12, 21971 - 21987.

Stoffelen, A., and D.L.T. Anderson, 1992 : Wind retrieval and ERS-1 scatterometer radar backscatter measurements. Reprinted from the World Space Congress, Washington, 28-08 - 5-09 1992.

Taconet, O., T. Carlson, R. Bernard and D. Vidal-Madjar, 1986 : Evaluation of a surface/vegetation parameterization using satellite measurements of surface temperature. J. Climate Appl. Meteor., 25, 1752 - 1767.

Thomas, D.R., and D.A. Rothrock, 1989 : Blending sequential SMMR and buoy data into a sea ice model. J.Geophys. Res., 94, C8, 10907 - 10920.

Tuzet, A, 1990 : A simple method for estimating downward longwave radiation from surface and satellite data by clear sky. Int. J. Rem. Sens., 11, 125 - 131.

Wetzel, P.J., and T. Chang, 1988 : Evapotranspiration from non-uniform surfaces. A first approach for short term numerical weather prediction. Mon. Wea. Rev., 116, 600 - 621.

Whitlock, C.H., W.F. Staylor, W.L. Darnell, M.D. Chou, G. Dedieu, P.Y. Deschamps, J. Ellis, C. Gautier, R. Frouin, R.T. Pinker, I. Laslo, W.B. Rossow and D. Tarpley, 1990 : Comparison of surface radiation budget satellite algorithms for downwelled shortwave irradiance with Wisconsin FIRE/SRB surface-truth data. Proceedings of the senevth conference on atmospheric radiation, San-francisco, published by the AMS, p237 - 242.

Wiegand, C.L., and A.J. Richardson, 1990 : Use of spectral vegetation indices to infer leaf area, evapotranspiration and yield : II. Results. Agron. J., 82, 630 - 636.

Wiegand, C.L., and A.J. Richardson, 1990 : Use of sprctral vegetation indices to infer leaf area, evapotranspiration and yield : I. Rationale. Agron. J., 82, 623 - 629.

Wu, J., 1992 : Near-nadir microwave specular returns from the sea surface — altimeter algorithms for wind and wind stress. J. Atmos. Ocean. Tech., 9, 659 - 666.