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Retrieving the Clear-Sky Vertical Longwave Radiative Budget from TOVS: Comparison of a Neural Network–Based Retrieval and a Method Using Geophysical Parameters

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ABSTRACT

At a time when a new generation of satellite vertical sounders is going to be launched (including the Infrared Atmospheric Sounder Interferometer and Advanced Infrared Radiometric Sounder instruments), this paper assesses the possibilities of retrieving the vertical profiles of longwave clear-sky fluxes and cooling rates from the Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) radiometers aboard the polar-orbiting National Oceanic and Atmospheric Administration satellites since 1979. It focuses on two different methodologies that have been developed at Laboratoire de Météorologie Dynamique (France). The first one uses a neural network approach for the parameterization of the links between the TOVS radiances and the longwave fluxes. The second one combines the geophysical variables retrieved by the Improved Initialization Inversion method and a forward radiative transfer model used in atmospheric general circulation models. The accuracy of these two methods is evaluated using both theoretical studies and comparisons with global observations.

1. Introduction

The earth's atmosphere is being observed continuously by a network of various instruments. The satellite radiometers are among the most important of these instruments, because their mesh in both space and time is by far the most fine. Since 1979, the National Oceanic and Atmospheric Administration (NOAA) has been bringing an ambitious program of polar sun-synchronous satellites into operation: measurements have been made by various onboard instruments every 12 h for most parts of the world and at most times. In particular, the Television and Infrared Observation Satellite—Next Generation (TIROS-N) Operational Vertical Sounder (TOVS) package combines a wide range of infrared and microwave sounding channels spread on three radiometers: High-Resolution Infrared Radiation Sounder, second generation—20 channels (HIRS-2); Microwave Sounding Unit (MSU)—four channels; and Stratospheric Sounding Unit—three channels. TOVS can provide

estimates of many geophysical variables: the three-dimensional temperature and moisture description of the atmosphere, a description of the surface (surface temperature and sea-ice detection), and various cloud properties (cloud type, cloud-top altitude, and effective cloudiness) (e.g., Smith et al. 1979; Susskind et al. 1997; Scott et al. 1999). The TOVS specifications also allow estimations of the longwave (LW) and shortwave boundary fluxes (e.g., Ellingson et al. 1989; Gupta 1989; Rossow and Zhang 1995; Mehta and Susskind 1999) and the three-dimensional LW structure of the atmosphere (Ellingson et al. 1994). Two main purposes motivate the production of these various datafields (the sounder brightness temperatures and the estimated geophysical and radiative parameters). The assimilation in numerical weather prediction schemes is the first one (e.g., Andersson et al. 1991). The second one is the analysis of climate, made possible by the continuity of the TOVS observations since 1979 (e.g., Wu et al. 1993; Wittmeyer and Vonder Haar 1994; Soden and Bretherton 1996; Stubenrauch et al. 1999c).

The current study focuses on two methodologies that have been developed at the Laboratoire de Météorologie Dynamique (LMD) for the estimation of the vertical LW radiative budget from TOVS. The first method relies on a nonlinear statistical method, the multilayer perceptron (MLP; Rumelhart et al. 1986), for directly linking the TOVS observed brightness temperatures to the LW fluxes: it will be referred to as N-TbFlux. The second meth-

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system (response or output) to another property of that system (predictor or input). These algorithms construct prediction rules by processing data taken from cases for which the values of both the response and the predictors have been determined. The most widespread technique is linear regression. For a long time, it has been applied to the estimation of fluxes and cooling rates from satellite data (e.g., Raschke et al. 1973; Gruber and Winston 1978; Tarpley 1979; Ellingson et al. 1994). The linear hypothesis on which these techniques are based limits the accuracy of such models.

Other statistical methods do not have the same drawback: for instance, MLP as defined by Rumelhart et al. (1986). MLP is among the artificial neural network techniques. It relies on processors, called formal neurons or neurons, with reference to the biological analogy. A neuron computes a weighted sum of its inputs and transfers this signal through a sigmoidal function (here the hyperbolic tangent). The neurons are gathered in layers. One or more “hidden” layers of neurons may be introduced between the input layer and the output layer. The parameters of this system are determined in an iterative way during a learning phase, by using a nonlinear regression: the so-called back-propagation algorithm. Since the beginning of the 1990s, MLP increasingly has been used at LMD for meteorology-related problems (e.g., Escobar-Munoz et al. 1993; Rieu et al. 1996; Chevallier et al. 1998). In particular, a preliminary study showed encouraging results in estimating the clear-sky flux profiles from TOVS brightness temperatures at nadir and over oceans (Ch  r  y et al. 1996a). Based on this approach, the complete N-TbFlux scheme has been elaborated.

b. Data preprocessing

N-TbFlux can estimate the radiative LW downward and upward flux profiles from TOA to the surface and from clear or cloud-cleared HIRS radiances. The cloud detection and cloud clearing of HIRS radiances are part of the 3I inversion. A summary of the 3I cloud detection, which is performed at HIRS spatial resolution (17 km at nadir), is given in Table 1 of Stubenrauch et al. (1999a). To reduce time-consuming computations, the HIRS radiances then are averaged separately over clear pixels and over cloudy pixels within 100-km by 100-km regions. If all pixels within such a region are cloudy, “cloud-cleared” radiances are inferred from the warmest pixels (Wahiche 1984; Chédin et al. 1985). The associated clear-sky LW flux profiles then can be computed from the clear or cloud-cleared HIRS radiances by the N-TbFlux method. At present, the 3I algorithm does not yet decontaminate the HIRS 4.57- μm channel from clouds, which is necessary for flux retrieval by N-TbFlux (see section 3d). In the near future, 3I will be extended for that purpose. Therefore, in the following article only real clear-sky situations are treated by N-TbFlux.

TABLE 1. The 20 pressure levels used for the radiative computations. They correspond to the pressure levels from the ECMWF operational general circulation model before 1991, when the surface pressure is equal to 1013 hPa.

| Level | Pressure (hPa) | Level | Pressure (hPa) |
|-------|----------------|-------|----------------|
| 19 | 0.0 | 9 | 453.1 |
| 18 | 20.0 | 8 | 546.7 |
| 17 | 40.0 | 7 | 642.4 |
| 16 | 60.8 | 6 | 735.3 |
| 15 | 86.2 | 5 | 820.4 |
| 14 | 119.7 | 4 | 892.8 |
| 13 | 163.6 | 3 | 948.5 |
| 12 | 219.2 | 2 | 985.6 |
| 11 | 286.8 | 1 | 1005.2 |
| 10 | 365.4 | 0 | 1013.0 |

c. *N-TbFlux* algorithm

The computation of the fluxes by N-TbFlux is split into three steps. The first step consists of adding small biases, or δs , to the radiances' equivalent brightness temperatures (Tb). These corrections account both for possible fluctuations of the radiometric calibration, including the satellite changes, and for errors in the radiance forward calculations performed for the setting of the neural network parameters (the learning phase), including those errors from the solar radiation effect. The δ values are automatically computed at LMD from collocations between radiosonde reports and TOVS observations (Scott et al. 1999); they are based on a 3-month running mean of the differences between the observations and the computations. The δs are less than 0.5% of the Tb values and the corresponding standard deviations are small in comparison with these biases.

After the δ correction is made, N-TbFlux selects a neural network among 60. As in the 3I inversion scheme, N-TbFlux uses 10 reference angles for the satellite viewing angle, from nadir to 60° , 19 surface pressures, and two types of surface: land and sea. For the sea, only the pressure level $P_s = 1013$ hPa is used. Chaboureau (1997) showed that the Tb variations behave uniformly for adjoining viewing angles: by way of biases, the Tbs for 10 viewing angles can be referred to only three angles, with an error comparable to the instrument noise. Thus, to take into account three viewing angles, 19 surface pressures for land, and one for sea, N-TbFlux uses 60 different neural networks. For a given situation, N-TbFlux selects the one that deals with the viewing angle, and also the surface type and pressure, closest to the situation. The chosen neural network computes the vertical clear-sky LW flux profiles. The vertical grid on which the fluxes are estimated is presented in Table 1. The atmosphere is divided into 19 layers from TOA to 1013 hPa; the fluxes are estimated at the corresponding 20 pressure levels.

d. Characteristics of the neural networks in N-TbFlux

The neural networks of N-TbFlux do not use all the available information of the TOVS observations. Some

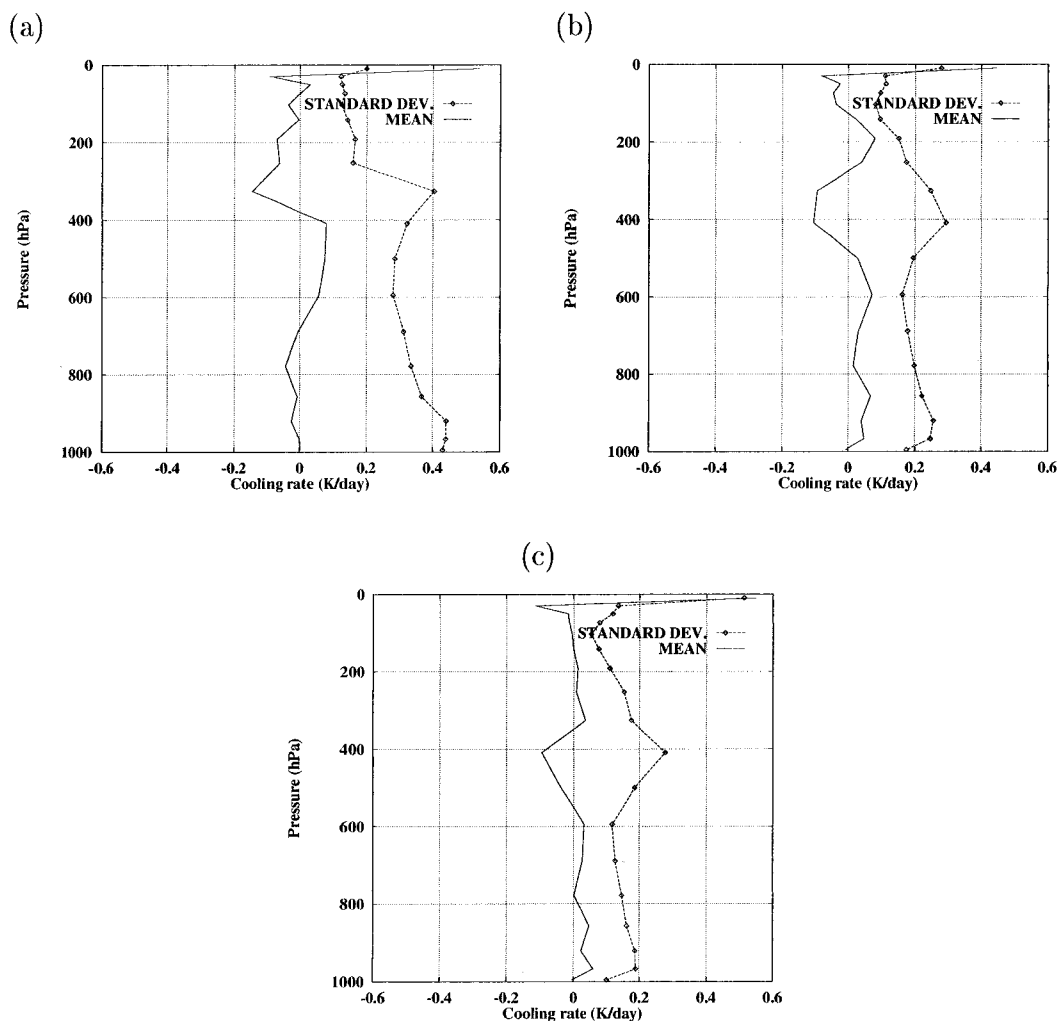


FIG. 1. Comparison between the computations of N-TbFlux from simulated TOVS Tbs and 4A from the corresponding geophysical parameters on 1032 radiosonde reports [cooling rates from N-TbFlux minus cooling rates from 4A (K day^{-1})]. Results are shown by airmass class: (a) tropical, (b) midlatitude, and (c) polar.

comparable to the spread of the computations from various radiative transfer models used in GCMs (Ellingson and Ellis 1991; Baer et al. 1996). Recall that models such as the ECMWF one or the 4A line-by-line model use the geophysical description of the atmosphere to compute the fluxes. Under clear conditions, the models tested by Baer et al. give cooling-rate profiles varying from one another by about 0.5 K day^{-1} at most pressure levels. Because the current validation uses synthetic cases and not real observations, it does not investigate two aspects of N-TbFlux: the δ correction and the accuracy of the radiative transfer model (RTM) used in the learning datasets to compute the reference fluxes (here the ECMWF wideband model). The δ correction is taken into account in sections 5 and 6. As far as RTM is concerned, Chevallier et al. (1998) showed on a similar problem that the neural network method can simulate at a given speed any RTM, including line-by-line ones,

with the same accuracy as that RTM. The possibility of using a line-by-line RTM for N-TbFlux has not been investigated yet, but the results therefore are expected to be similar to those presented here.

The high values of the computed LSNF error for N-TbFlux probably are related to the poor vertical resolution of HIRS in the lower atmosphere rather than to a limitation of the neural network-based approach. Indeed, according to Gupta (1989), 86% of the downward radiation arriving at the surface comes from the lower 50-hPa layer, and the sensitivity of the HIRS channels to such an atmospheric layer is known to be weak. That is why previous studies with different fast methods also reported high uncertainty in the estimation of the downward LW fluxes at the surface; Gupta et al. (1992) show an uncertainty of about 20 W m⁻², and Ellingson et al. (1994) report an error of about 10 W m⁻².

surface parameters (Chédin et al. 1985; Scott et al. 1999). It makes use of the TIGR databank in which a first solution to the inversion is selected by a pattern recognition approach.

Within the framework of the NOAA/National Aeronautics and Space Agency (NASA) Pathfinder program, 8 yr of TOVS data (*NOAA-10* and *NOAA-12*) already have been processed by the 3I algorithm. The 3I–Pathfinder data are organized in a 1° lat \times 1° long grid. Temperature profiles, originally retrieved for 28 pressure layers from 1013 to 10 hPa, are archived on a nine-layer vertical grid. The layers are bounded by the following standard pressure levels: the surface, and 850, 700, 500, 300, 100, 70, 50, 30, and 10 hPa. This pressure grid was chosen according to the performances of the TOVS sounder, which were issued from its specifications. For instance, in a data assimilation context, Thépaut and Moll (1990) showed that the use of HIRS and MSU observations provides no more than seven independent statistical pieces of information for the temperature and water vapor. Chevallier (1998) confirmed that, for the current study, the restriction from 28 to nine layers for the temperature description does not significantly affect the results. The vertical distribution of water vapor appears in the 3I–Pathfinder dataset under the form of integrated quantities over five layers bounded by levels at the surface and at 850, 700, 500, 300, and 100 hPa (Chaboureaud et al. 1998). The characteristics of the clouds (effective cloud emissivity, cloud-top pressure and temperature, and cloud type) also are retrieved (Stubenrauch et al. 1999b). All these quantities are available in the 3I–Pathfinder dataset on a daily, 5-day (pentad), and monthly basis, for the morning (AM) and the evening (PM) overpasses of the satellite.

c. From the 3I-retrieved variables to the radiative transfer model

The LW flux profiles corresponding to the 3I-retrieved geophysical parameters are obtained by applying the ECMWF wideband radiative code, which is used also for the setting of N-TbFlux parameters. For a particular atmospheric situation (clear as well as cloudy), the radiative transfer model computes both the clear and the cloudy components of the LW flux profiles. The main inputs required for the computation of the clear-sky component are the temperature, water vapor, and ozone profiles and the surface temperature. Most of these quantities are available from the 3I outputs after some postprocessing. For water vapor, a crude assumption has to be made to estimate the mixing ratio vertical profile from the 3I-integrated quantities; in the current study, it is assumed that the relative humidity does not change inside the five retrieval layers. This assumption is discussed in section 4e. The ozone profile, which is not retrieved here from TOVS, comes from the climate dataset of McPeters et al. (1984). For a better estimation of the vertical integrals in the radiative computations,

the vertical resolution of the atmospheric profiles has been increased by interpolation from the nine 3I-Pathfinder layers to the 19 layers from Table 1.

This process for the estimation of the LW fluxes from TOVS requires that the 3I algorithm succeed in retrieving all the needed parameters from the TOVS Tbs: the temperature and water vapor profiles, and the surface temperature. Chaboureau (1997) indicates that all the needed parameters are retrieved for about 90% of the clear-sky data, but this score decreases to about 75% for the partly cloudy situations and to about 10% for the overcast ones. For overcast situations, the 3I retrieval scheme rejects the data when there is more than 60% cloudiness on each HIRS pixel within the retrieval grid box. These gaps have not been filled.

d. Computed quantities

Because the water vapor profiles used in the forward radiative transfer computations come from only five coarse layers, the 19 layers shown in Table 1 obtained from interpolation do not give additional information on the vertical thermodynamic structure of the atmosphere. Thus, the 3IFlux cooling rates have been averaged on six coarse layers. The pressure levels at the boundaries are the surface, and 950, 850, 500, 300, 100, and 0 hPa. They correspond approximately to the water vapor layers. The two layers 850–700 hPa and 700–500 hPa have been merged. The 3I–Pathfinder surface–850 hPa layer has been divided into two sublayers to take into account, over the oceans, the dominating influence of the surface temperature in the boundary layer.

e. Sensitivity studies to input data uncertainties

To estimate the accuracy of the fluxes computed from 3IFlux, a series of sensitivity tests were performed. These tests consist in perturbing the geophysical variables used as inputs to the ECMWF radiative code rather than perturbing the Tbs, as was done for N-TbFlux validation. This method indirectly enables the uncertainty in the δ computation, used by 3I as well as by N-TbFlux, to be taken into account. The values of the perturbations have been chosen to be of the same order of magnitude as the differences observed (plus or minus one standard deviation) between 3I-retrieved temperature or water vapor profiles and radiosonde measurements of the same quantities (Scott et al. 1999). The authors are aware that because of the irregular spread of the radiosoundings, some kinds of errors may be poorly documented. The estimated uncertainties in the temperature profiles are about 2.0 K in the higher and lower atmosphere and about 1.5 K in the middle atmosphere. For the water vapor, they reach 40% in the 500–300-hPa layer and decrease to about 25% in the 1013–850-hPa layer. These numbers refer to standard deviations, because the retrieved quantities are nearly unbiased. Because of its effect on infrared radiation, cloudiness is the major fac-

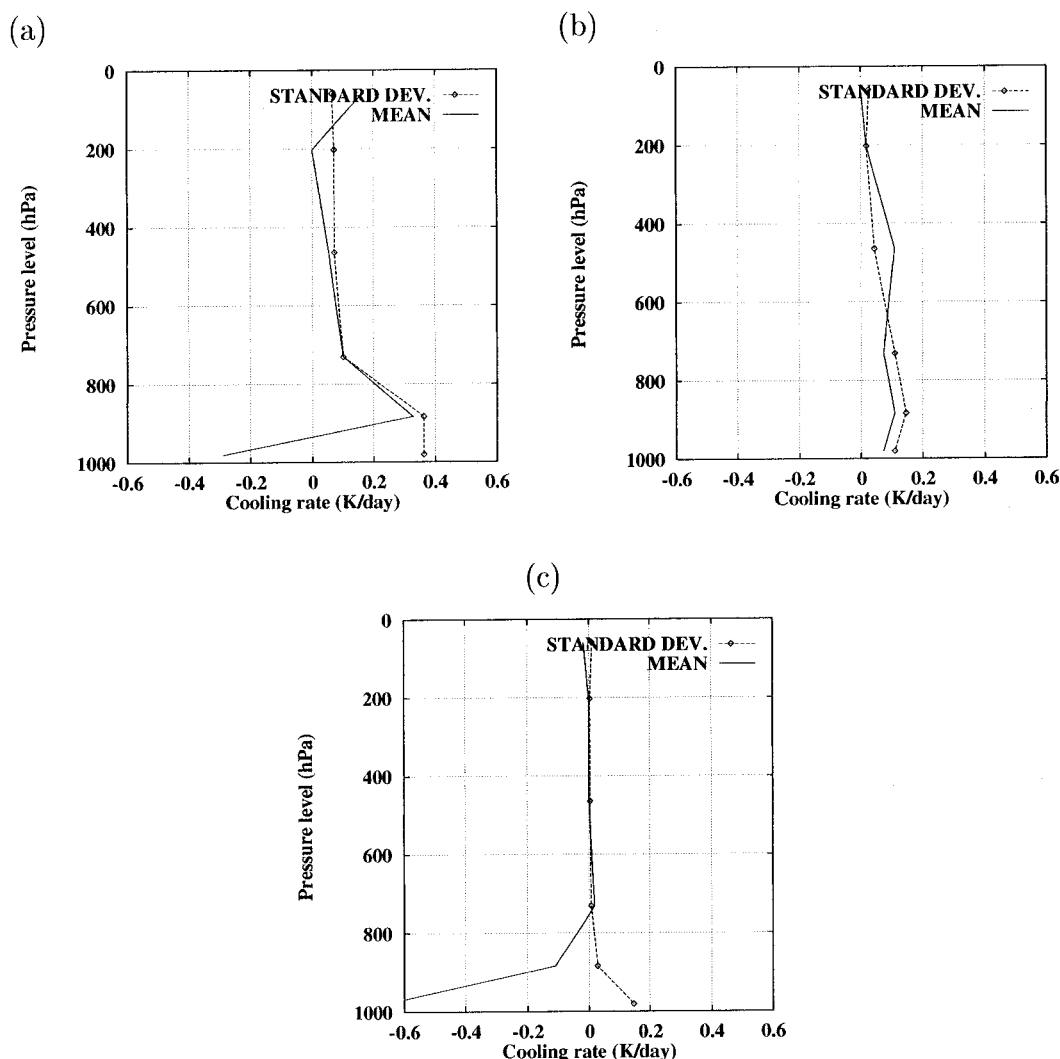


FIG. 3. Global mean change and associated standard deviation in monthly mean cooling rates (K day^{-1}) produced by changing the input variables to the radiative transfer model by the amount indicated in the text: (a) temperature only, (b) water vapor only, and (c) surface temperature only.

errors are not correlated with the previous ones but rather add to them. Nevertheless, as the values of the fluxes, and of the cooling rates between the 300-hPa level and the surface, are nearly unbiased, the crude assumption relating to water vapor should not affect the climatological signals of these variables.

5. Comparisons of computed fluxes based on radiosonde reports

A comparison has been made between flux computations from N-TbFlux, from 3IFlux, and from direct computations with the ECMWF wideband model using radiosonde archives from NOAA/NESDIS (the DSD5 archive; Uddstrom and McMillin 1993) currently used at LMD for validation of the 3I-retrieved variables. The current study uses the *NOAA-10* collocation files from

September 1987 to October 1989 restricted to oceanic areas and to clear-sky conditions, as determined by the 3I retrieval method. Eight-hundred and thirteen satellite–radiosonde collocated situations were found matching this criterium, 756 of which had all the needed 3I-retrieved geophysical variables. Recall that the changes in spectral characteristics from *NOAA-11* to *NOAA-10* are taken into account in both 3I and N-TbFlux by the δs (see section 3c).

The radiosonde-based computations will be viewed as the reference computations. One has to keep in mind, however, the uncertainties induced by the radiosonde measurements (e.g., McMillin et al. 1992; Luers and Eskridge 1998) and by the collocation window (100 km, 3 h). Moreover, as was said before, the surface skin temperature has not been archived in the DSD5 files. In the present computations, the sea surface temperature

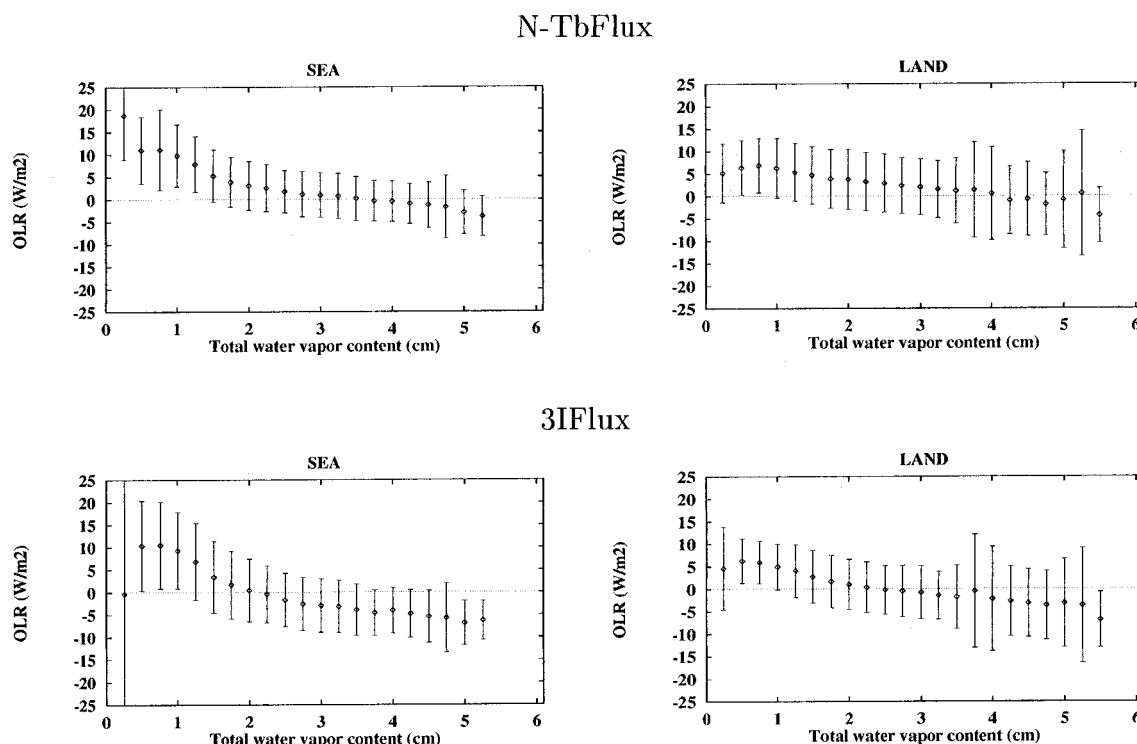


FIG. 6. As in Fig. 5 but the difference is expressed as a function of total water vapor content. The definition of the total water vapor content comes from the 3I retrieval scheme. The standard deviation for 3IFlux over the sea (left, bottom) for contents smaller than 0.3 cm reaches 32.7 W m^{-2} .

ing, both methods are characterized by a marked trend, with positive biases for small water vapor contents and negative biases for large contents. This trend appears at any latitude throughout the 4 months (result not shown). This trend is not observed in the previous radiosonde-based comparisons (result not shown).

The common features of N-TbFlux and 3IFlux that may explain such behavior are the use of the δ s and the use of the ECMWF wideband model. For the δ s, such an obvious water vapor-dependent estimation error is unlikely, because it also would have affected the 3I retrievals and appeared in the 3I validation. According to its validation against line-by-line computations (Chevallier 1998), the effect of the high level of parameterization of the ECMWF code on its accuracy should be limited to 2 W m^{-2} , if one admits that the current water vapor continuum modelizations are accurate. Similar tendencies between computed OLR and ERBE OLR, as a function of total water vapor content, have been observed by several authors: Collins and Inamdar (1995), using radiosonde data, and Slingo et al. (1998), using the ECMWF meteorological analysis. The ERBE S8 processing may be responsible for this effect. The measured ERBE radiances followed two processes; the first one corrected them from the spectral filter effects, and the second one converted them into fluxes (Smith et al. 1986). Because the trend also is apparent when looking at the corrected radiances (results not shown),

the spectral correction should be the only cause of the problem.

To conclude, with the exception of situations for which water vapor content is lower than 0.3 cm, OLR computed by N-TbFlux and 3IFlux are characterized by an uncertainty that is comparable to that of the ERBE instantaneous product.

c. Use of SSM/I data in the 3IFlux process

The deficiency of both 3IFlux and N-TbFlux for low water vapor contents is likely to be linked with the characteristics of the TOVS instrument. Indeed, infrared sounding is limited by known weaknesses induced by the form of the radiative transfer equation at the corresponding wavenumbers; when the contrast between the surface skin temperature and the temperature of the lower atmosphere is low, there is no sharp infrared weighting function that peaks in the boundary layer (e.g., Chérut et al. 1995). This case is true for HIRS: too-humid retrievals of precipitable water have been observed in the subtropical maritime stratocumulus regions off the coast of California, Chili, Mauritania, and Angola (Stephens et al. 1994; Chaboureaud et al. 1998), over which the vertical lapse rate is chiefly low. Atmospheric water vapor observations from satellite passive microwave imagers such as, for instance, Special Sensor Microwave Imager (SSM/I) on board of the De-

of the results from the current radiative transfer codes used in GCMs, for OLR and vertical cooling rates. In the case of 3IFlux, the uncertainty of the radiative transfer model has not been studied here and adds to the uncertainty estimated in the current study. Comparisons at TOA with the ERBE instantaneous OLR determinations showed similar uncertainties but smaller biases than in the ERBE process, except for total water vapor contents lower than 0.3 cm. Because of the HIRS poor resolution in the lower atmosphere, higher uncertainty is found for LSNF, up to 10 W m^{-2} standard deviation with N-TbFlux. The 3IFlux and N-TbFlux are both parameterized methods and do not add significant computational burden to the current retrieval process of the TOVS Tbs: one month's worth of data is processed by N-TbFlux in 300 s (central processing unit time) and by 3IFlux in 2200 s (central processing unit time), on a Cray C98 computer.

In the various validations presented here, N-TbFlux performs better than 3I-Flux, with smaller biases in comparison with other data. This difference may be due to the capacity of the neural network-based method to adapt optimally to any vertical pressure grid for the retrieved fluxes, whereas 3I-Flux interpolates between three different grids: the one of the 3I-retrieved temperature, the one of the 3I-retrieved water vapor contents, and the one of the flux computation. Nevertheless, the 3IFlux methodology may be used more easily for climate studies, for which the significance of the signals in the time series has to be asked. Indeed, because of the current lack of high-quality global data of radiative fluxes and cooling rates, the accuracy monitoring of N-TbFlux may be delicate. In comparison, 3IFlux allows for easier quality checks, through the various operational measurements of water vapor, temperature, and surface temperature. As a consequence, as illustrated with the experiment with SSM/I data, 3IFlux allows for bias correction of the final product, whereas the N-TbFlux biases are controlled by the δ s only. In the near future, with the development of flux measurements, with the improvement in the TOVS instrument and in the Advanced TOVS version, and with new infrared sounders such as the Infrared Atmospheric Sounder Interferometer and Advanced Infrared Radiometric Sounder, these two methodologies should produce more accurate results.

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