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ASSESSMENT OF ENERGY BUDGET IN WEATHER FORECASTING GENERAL CIRCULATION MODELS

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A comprehensive data set, which has been archived during Enhanced Observing Period 3 (EOP3- from 1 October 2002 to 30 September 2003) of the Coordinated Enhanced Observing Period, is used to assess the representation of surface energy budget in five operational weather forecasting General Circulation Models (GCMs). It is found that shortwave downward radiation is generally over-estimated and downward longwave radiation is under-estimated. Since the error in shortwave downward radiation is dominant in most of the models, net radiation is over-estimated in all the models. Turbulent heat fluxes are not well modeled by all the GCMs and there are systematical errors that might be attributed to incorrect model parameter setting or model physics. The GCMs generally over-predict nighttime downward sensible heat fluxes but under-predict diurnal ranges of surface-air temperature difference, showing that heat transfer resistances are under-predicted. This problem is especially severe for arid and semi-arid regions. Also, a model without explicit representation of vegetation processes is not able to reproduce observed surface energy budget.

Key Words : *GCM, CEOP, Radiation, Surface energy budget , Aerodynamic Resistance, Prediction skill*

1. INTRODUCTION

The accurate weather and climate predictions are crucially important for planning our day-to-day activities. The Coordinated Enhanced Observing Period (CEOP) is a coordinated international activity aimed to establish an integrated global observation system. It is an element of World Climate Research Programme (WCRP) that was initiated by international efforts of the Global Energy and Water Cycle Experiment (GEWEX). CEOP provides a golden opportunity for weather and climate researchers to use enhanced observations to better document and simulate water and energy fluxes and reservoirs over land on diurnal to annual scales, to better predict these up to seasonal scale for water resource management, and to document seasonal march of the monsoon systems, their driving mechanisms, and their physical connections.

General Circulation Models (GCMs) play a major role in water and energy simulation and are today the basis of the weather and climate prediction around the world. In order to enhance GCM performance, diagnosing the details of model errors by comparing GCM output with observation would be the basis for improving the representations of key processes[1]. Even though many studies and evaluations have been done in the past and presently continuing such as AMIP (Atmospheric Model Inter-comparison Project)[2] and PILPS (Project for Inter-comparison of Land-Surface Parameterization Schemes)[3], CEOP provides a unique platform through the Enhanced Observing Periods (EOP) with comprehensive data sets for evaluating model performance and uncertainties for individual climate regions. Within the framework of the CEOP project, some projects[4] have been proposed to take advantage of the extensive CEOP collection in order to better understand and quantify the uncertainty of model output. Some inter-comparisons have been implemented for short periods[5], individual sites[6], single parameters[7], or single models. These studies are not only important for detecting model deficiency and thus improving the representations of key processes, but also contribute to data users for identifying appropriate data from rapidly increasing database for their own studies.

Within the framework of a full annual cycle, multi-sites, multi-variables, and multi-model output, this paper presents an evaluation of surface energy budget in five operational weather forecasting GCMs through comparisons and inter-comparisons between in situ data and model data. This study is distinct from early inter-comparisons efforts in three aspects. First, it is the first inter-comparison study for current operational weather forecasting GCMs that have higher spatial-resolutions than AMIP GCMs and simulations are reinitialized six hourly or daily for operational weather forecasting, so they are expected to have better prediction skill than AMIP GCMs. Second, CEOP reference sites were selected so that these sites can cover a variety of climate regimes and the observations include high-accuracy measurements of major variables involved in hydro-meteorological studies (surface, subsurface, and atmospheric variables), making it is possible to identify effectiveness and deficiencies of parameterization schemes of physical processes. Third, CEOP archives high temporal-resolution data of field observations (hourly or half hourly) and specialized model output (hourly or three hourly). These high temporal-resolution data provide an opportunity to study diurnal variations of variables of interest.

2. DATA AND METHODOLOGY

Table 1 Basic information of CEOP flux reference sites and observed rainfall during EOP3. Italic site only has data of six months.

Reference site	Lat. (N)	Lon. (E)	Ele. (m)	Land use	Rainfall (mm)
Lindenberg	52.17	14.12	112	grass	431
Cabauw	51.97	4.93	-1	grass	690
SGP	36.61	-97.5	313	grass	617
Bondville	40.01	-88.3	300	cropland	679
Fort Peck	48.31	-105	800	grass	56
Oak Ridge	*35.96*	*-84.3*	*275*	*mixed forest*	*832*
Tongyu	44.4	122.9	184	grass	310
Manaus	-2.61	-60.2	130	forest	2296
Santarem	-3	-55	194	tropical fores	1588

Table 2 Major characteristics of CEOP-participating GCMs. MOSES: Meteorological Office Surface Exchange Scheme.

Model	Horizontal Resolution	Land Surface Scheme	Output Interval
BMRC	T239L29 $\Delta x \sim 80$ km	Bucket hydrology	1 hr
ECPC	T62L28 $\Delta x \sim 280$ km	OSU LSM ver. 2	3 hrs
JMA	T213L40 $\Delta x \sim 60$ km	Simple Biosphere	1 hr
NCEP	T254L64 $\Delta x \sim 50$ km	Simple Biosphere	3 hrs
UKMO	0.83x0.56 deg.	MOSES	3 hrs

Within the climate system, the earth's surface is the place where active energy exchanges takes place. It is therefore essential to improve numerical models' capability in simulating surface energy fluxes for different climatic regimes. CEOP has defined 35 reference sites, where field observations were made by research institutes and national services worldwide. Currently, the data for the EOP3 (from 1 October 2002 to 30 September 2003) are the most widely archived one, among of which turbulent flux data at nine sites are available. Table 1 shows basic information of the nine flux measuring reference sites. This study is based on EOP3 data set at these nine sites, including in situ data and corresponding Model Output Location Time Series (MOLTS) from five Numerical Weather Prediction (NWP) centers.

EOP3 archived model data are from BMRC (Bureau of Meteorology Research Centre, Australia) Operational Global Medium Range Prediction Model, ECPC (Experimental Climate Prediction Center, The Scripps Institution of Oceanography, USA) Seasonal Forecasting Model (SFM), JMA (Japan Meteorological Agency) Global Spectral Model (GSM), NCEP (National Centers for Environmental Prediction, USA) Global Forecast System (GFS), UKMO (Met Office, UK) Global Unified Model. Major characteristics of these models are shown in Table 2.

In order to smooth spatial variability of surface variable as addressed by early studies[5),6)], monthly and annual mean values and diurnal variation and composite value are considered instead of hourly or 3-hourly, or daily values at individual sites. Yang et al.[8)] summarized the results of a model inter-comparison study, based on multi-site and multi-month composite values of radiation, energy, water budget, and the diurnal cycle of precipitation. In this study, we focus on energy budget and give more detailed analysis at individual reference sites. Before the evaluation, modeled air temperature is corrected with a lapse rate of 0.0065 K m^{-1}, and longwave radiation is corrected with an addition of 2.8 W m^{-2} per 100 m following Wild et al.[10)], when model elevation is different from in situ elevation.

3. RESULTS AND DISSCUSION

(1) General evaluation

Fig.1 shows the direct comparison of annual mean value of energy fluxes at individual sites for the five GCMs. Manaus is not included in Fig. 1 because many data are missing. All the models show a clear tendency of over-predicting Downward Shortwave

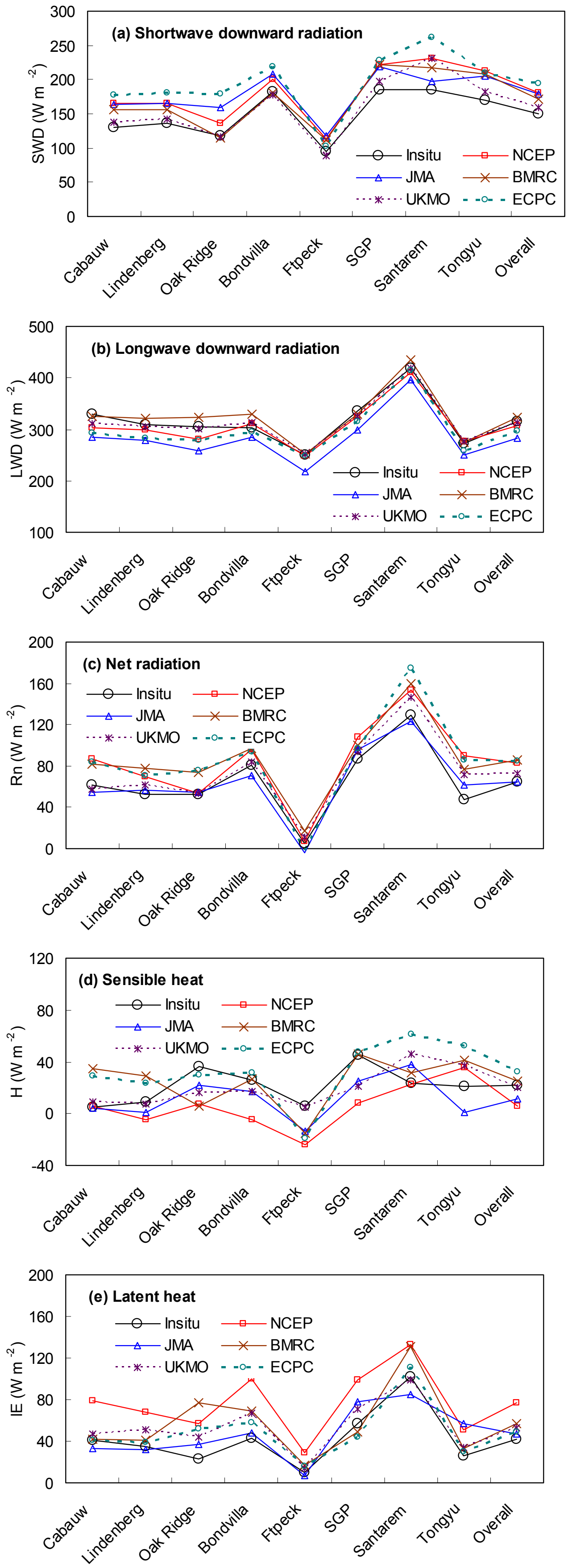

Fig.1 Comparison of annual mean value at each site and overall (a) Shortwave downward radiation, (b) Longwave downward radiation, (c) Net radiation, (d) Sensible heat, (e) Latent heat.

Radiation (SWD). They also tend to under-predict Downward Longwave Radiation (LWD) at all the sites except BMRC model. Among the models, UKMO gives minimum deviations while JMA and ECPC show relatively large deviations from the observations for both downward shortwave and longwave radiation components. Net radiation simulated by UKMO, JMA and ECPC have a good agreement with observations and the other models over-predict it at most of the sites. It is interesting and notable that even though JMA and ECPC show relatively large biases in both downward radiation components, they give small biases in net radiation prediction, as a result of compensation of the errors in SWD and LWD.

Similar over-prediction of SWD and under-prediction of LWD have been reported in early studies [9),10)]. For SWD, under-estimation of clear-sky absorption and cloud absorption in the model was suggested [11),12)]. For LWD, Wild et al. [10)] suggested that LWD schemes themselves should play a major role for the under-estimation. On the other hand, the error in surface radiation might be also due to under-prediction of cloudiness[13)]. Since CEOP in situ data did not include cloudiness information, it is impossible to directly evaluate model cloudiness. Lack of coudniess data is a major gap in the CEOP data, and CEOP next phase has to undertake with the present observational gaps in the in situ data.

Fig.1 (d) and (e) shows the simulated sensible heat and latent heat at each sites, and Table 3 shows the statistical errors over all the sites. The energy fluxes simulated by JMA and UKMO are relatively better than the other models for most of the sites. ECPC much over-predicts sensible heat fluxes. NCEP much under-estimates sensible heat and over-estimates latent heat at most of the sites. This is probably associated with the over-prediction of precipitation (not shown here).

Table 3 Mean Bias Error (MBE) and Root Mean Square Error (RMSE) of surface energy budget over all the sites.

	MBE (W m^{-2})			RMSE (W m^{-2})		
	Rn	H	lE	Rn	H	lE
BMRC	12.3	8.4	14.5	26.4	51.5	49.2
ECPC	2.6	20.1	6.5	28.9	59.7	28.3
JMA	-5.3	-6.8	6.3	24.4	22.2	26.6
NCEP	14.8	-14.3	37.9	31.5	28.4	44.9
UKMO	4.6	-0.7	12.4	19.1	25.3	31.9

(2) Seasonal march of energy fluxes

It is found that SWD is over-estimated and LWD is under-estimated by almost all the models in many sites during all the seasons. Therefore, their errors are not random one (not shown).

As an example, Fig.2 shows the seasonal variations of heat fluxes at Lindenberg site. ECPC produces too strong sensible heat fluxes during the summer period and the modeled sensible heat fluxes largely deviate from the observation (Fig.1). On the other hand, the latent heat fluxes produced by ECPC have a relatively good accuracy in the summer compared to other models. Similarly, BMRC also produces too strong sensible heat fluxes. In particularly, the modeled latent heat fluxes do not follow the observed seasonal variation (i.e., high values during the summer period). Therefore, BMRC has encountered a serious problem in the partitioning of available energy into sensible heat and latent heat fluxes during the summer period. Since BMRC adopts a bucket hydrological model that excludes the biospheric processes, the error is thus caused by the model itself. This confirms that a model without explicit representation of vegetation processes cannot well produce the partitioning of available energy into sensible and latent heat fluxes.

Similar results are found for other flux sites and will not be shown here.

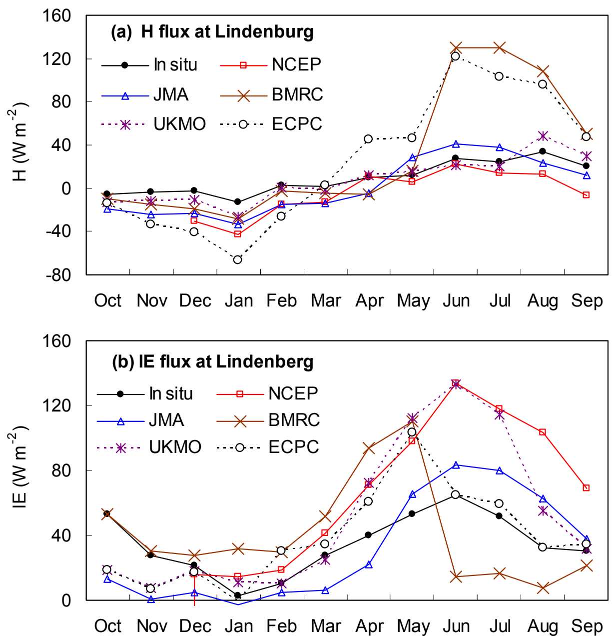

Fig.2 Turbulent heat fluxes at Lindenberg site.

(3) Composite diurnal cycle of energy budget

Fig.3 shows the multi-site composite diurnal variations of surface energy fluxes. It is clear that ECPC produces much stronger sensible heat and NCEP produces much stronger latent heat fluxes during the daytime. All the models predict reasonable phases of net radiation and sensible heat fluxes, but the peaking time of latent heat fluxes are predicted too late. A significant over-prediction of nighttime downward heat fluxes occurs among all the models. This problem is due to the over-prediction of heat transfer efficiency. In order to clarify the problem, the diurnal variation of the surface-air temperature difference is analyzed. Fig.4 shows the monthly-mean diurnal variation of surface-air temperature difference at a semi-arid (Tongyu) site. It is very clear that all the models under-predict its diurnal range. This under- prediction is more significant for arid and semi-arid sites than for forest sites (not shown). We calculate heat transfer resistances according to the following formula:

$$r_H = \frac{\rho C_p (T_s - T_a)}{H} \quad (1)$$

Where r_H (s m^{-1}) is the aerodynamic resistance, ρ is air density (kg m^{-3}), C_p the specific heat of air at constant pressure (J kg^{-1} K^{-1}), T_a (K) is the air temperature at a reference height (z) above the surface, and T_s (K) is the surface temperature.

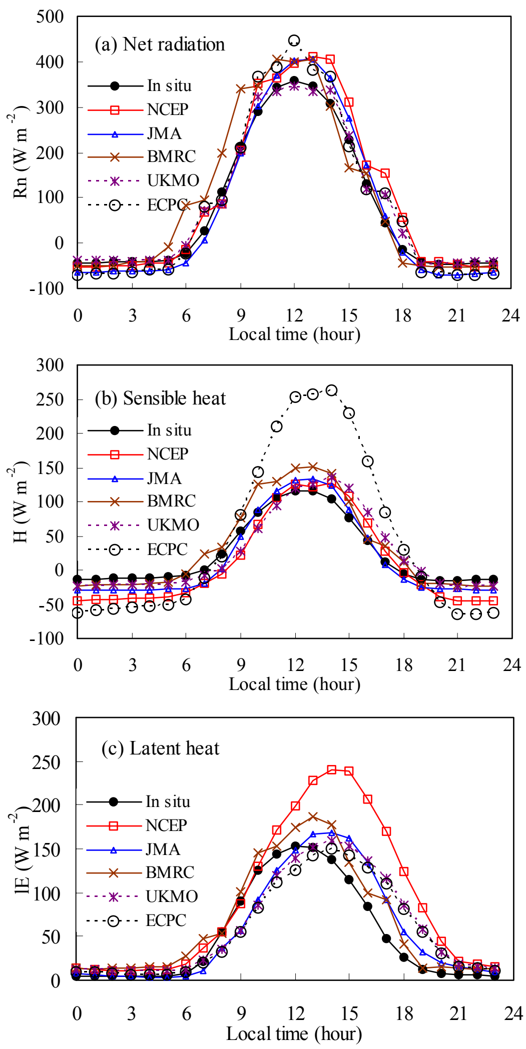

Fig.3 Composite diurnal variation of surface energy budget from in situ data and GCMs at nine flux sites.

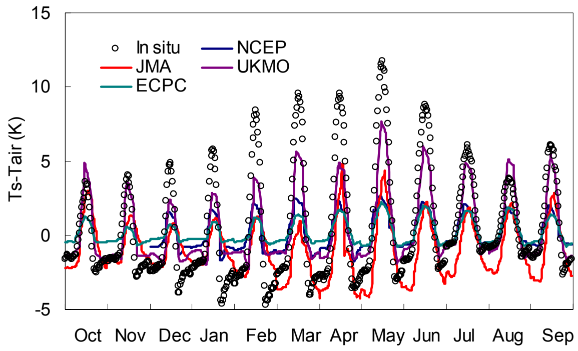

Fig.4 Monthly-mean diurnal variation of (Ts-Ta) at Tongyu site.

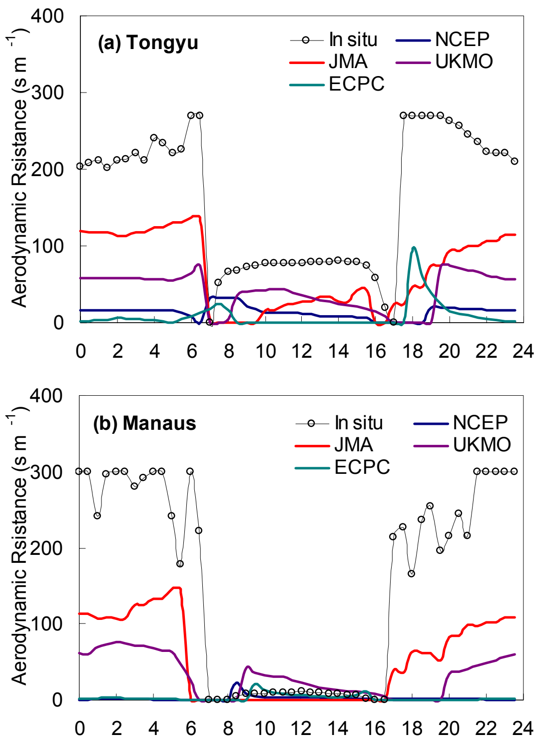

Fig.5 Annual-mean diurnal variation of aerodynamic resistance at (a) Tongyu, (b) Manaus sites.

Fig.5 shows the annual mean diurnal variation of the aerodynamic resistance at Tongyu (a semi-arid site) and Manaus (an evergreen forest site). In the daytime, the observed aerodynamic resistances are smaller compared with the nighttime observed one, indicating the daytime solar heating leads to high heat transfer capability over the land surface because of the breakup of early-morning stable boundary layers. In the nighttime, surface radiative cooling stablizes boundary layers and reduces the heat transfer capability or increases heat transfer resistance.

Fig.5 (a) clearly shows the resistances at Tongyu site are much under-predicted in all the GCMs, which in turn results in small surface-air temperature gradients in Fig.4. However, the resistances at Manaus site (the evergreen forest site) are predicted reasonably in the daytime. Therefore, the resistances are not well simulated by all the models in arid and semi-arid regions, compared to forest areas. This under-prediction of aerodynamic resistance for heat transfer can cause incorrect energy partitioning in simulations.

(4) Feedback to air temperature and humidity simulation

The above analysis shows that the operational weather forecasting GCMs are not able to produce observed surface energy budget. The errors in energy partitioning, in turn, affect the accuracy of near-surface variables such as air temperature and air humidity. For example, Fig.6 shows the simulated air temperature and humidity at Lindenberg site. During the summer period, ECPC and BMRC simulated much higher air temperature and lower humidity in this site. As shown in the above section, ECPC and BMRC systematically over-predict sensible heat fluxes for the summer period. Because more energy and less vapor are transferred into the surface boundary layer, this incorrect energy partition would result in higher air temperature and lower air humidity, as shown in Fig. 6. Similar feedback in both ECPC and BMRC has been found in some other sites too (not shown here).

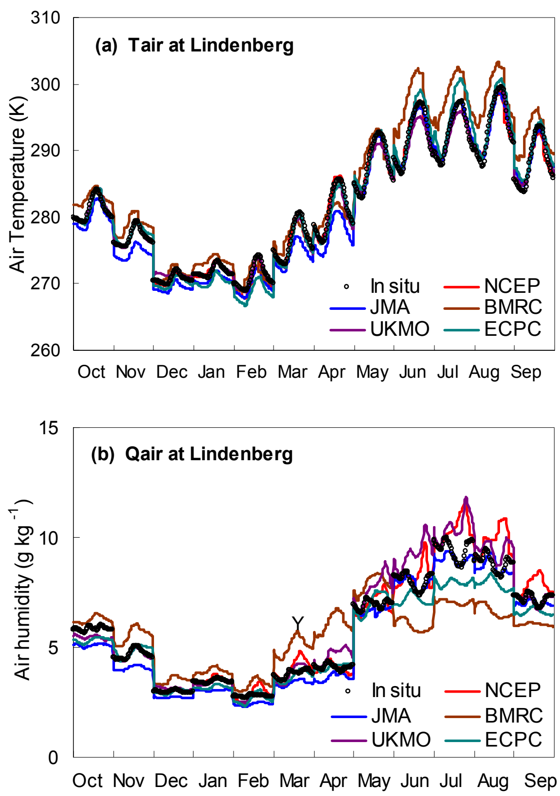

Fig.6 Air temperature and humidity at Lindenberg site.

5. CONCLUSION

Based on data archived in CEOP, this study has investigated the simulated surface energy budget components and the causes for the uncertainties in five operational weather forecasting GCMs. The following conclusions are suggested.

The over-estimation of downward radiation and under-estimation of downward longwave radiation have been found in most of the models. JMA and ECPC show much higher deviation for downward shortwave and longwave radiation, but the cause needs further invesigation because cloudiness data are not available. Almost all the models over-estimate net radiation. Due to counteract of errors in downward radiation components, JMA and ECPC produce small biases in net radiation simulation, though they produce high biases in both downward components,.

For surface energy budget, JMA and UKMO predict surface energy fluxes better than the other models. ECPC predicts too strong sensible heat fluxes during the summer period at most of the sites while reasonable latent heat fluxes. BMRC over-predicts sensible heat fluxes while under-predicts latent heat fluxes during the summer period. Since BMRC adopts a bucket hydrological scheme for its land surface processes and no vegetation information is described in the model, this inaccurate energy partitioning should be caused by the LSM itself. NCEP tends to over-predict latent heat fluxes and to under-predict sensible heat fluxes. The over-prediction of latent heat might be associated with its over-prediction of precipitation.

All the operational GCMs over-predict downward sensible heat fluxes in the winter season and in the nighttime. This error is related to the under-prediction of heat transfer resistances, which in turn results in the under-prediction of diurnal range of surface-air temperature difference. The resistances heavily depend on the setting of momentum roughness lengths and thermal roughness lengths. Relationships between the two lengths are derived from field experiments in flat and small areas, where momentum loss is not affected by meso-scale topographic undulations. Such undulations in a GCM grid are common and may strongly enhance momentum loss while contribute little to heat transfer. Accordingly, a large ratio of momentum roughness length to thermal roughness length is required in order to model realistic wind speed and heat fluxes, and such a large ratio can be quite different from patch-scale experiments-based formulas. Therefore, applications of those formulas in GCMs are not so direct and need upscaling. In addition, all the models produce a too late peaking time of latent heat fluxes, which needs further investigations in the future.

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