The ultimate meteorological question from observational astronomers: how good is the cloud cover forecast?

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ABSTRACT

To evaluate the capability of numerical cloud forecasting as a meteorological reference for astronomical observations, we compare the cloud forecast from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model for total, layer and convective cloud with normalized satellite observations from the International Satellite Cloud Climatology Project (ISCCP) for the period of 2005 July–2008 June. In general, the model forecast is consistent with the ISCCP observations. For total cloud cover, our result shows the goodness of the GFS model forecast, with a mean error within ±15 per cent in most areas. The global mean probability of <30 per cent forecast error (polar regions excluded) declines from 73 per cent to 58 per cent throughout the 180-h forecast period and is more skilled than the ISCCP-based climatology forecast up to $\tau \sim 120$ h. Comparison using layer clouds reveals a distinct negative regional tendency for low cloud forecast and a questionable positive global tendency for high cloud forecast. Fractional and binary comparisons are performed on the convective cloud forecast and it is revealed that the GFS model can identify less than half of such cloud. In short, our result suggests that the GFS model can provide satisfactory worldwide total cloud forecasts up to a week ahead for observation-scheduling purposes, but layer and convective cloud forecasts are less reliable than the total cloud forecast.

Key words: atmospheric effects – site testing.

1 MOTIVATION

The most important prerequisite of most successful astronomical observations, particularly optical observations, is without doubt a cloudless sky (see the story of Guillaume Le Gentil in the 1761/69 Transit of Venus, cf. Sawyer Hogg 1951, for a rather unlucky example). However, forecasting cloud cover has been difficult for a long time, as it is limited by our theoretical understanding of mesoscale circulation (i.e. modelling) and computation ability. Numerical simultaneous cloud-cover forecasts for astronomical observations were not useful for practical purposes until the very end of the 20th century.

In the meteorological context, cloud plays a key role in the radiation balance of the Earth and is widely accepted to be the main source of uncertainty in global weather predictions (cf. Stubenrauch et al. 1999; Stephens 2005). It has garnered much attention from the atmospheric sciences community, both from modelling groups and from observational groups. The attempt to ‘parametrize’ cloud activity started in the 1980s (cf. Sundqvist, Berge & Kristjánsson 1989, and references therein). Several cloud schemes have been proposed since then, followed by ground- and space-based evaluation with the aim of achieving refinements (e.g. Hinkelman, Ackerman & Marchand 1999; Luo, Krueger & Moorthi 2005; Yang et al. 2006).

Although many amateur and professional observatories have taken advantage of open access to the output of major numerical weather models for a decade, the reliability of such forecasts is poorly understood. The meteorology community is mostly interested in particular mesoscale events and/or particular regions and pays relatively little attention to the model performance over broader environments, while there are only two studies from the astronomy community that have investigated this topic: that of Erasmus & Sarazin (2001), who suggested that only 15–25 per cent of cloudy nights at European Southern Observatory sites could be identified by the European Centre for Medium-Range Weather Forecasting (ECMWF) model, and our earlier study (Ye 2011), which suggested a high detection rate accompanied by a moderate false-alarm rate from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) model, based on cloud observations from several astronomical observatories. Even so, as the two studies are both limited in spatial densities and scales, investigations of numerical cloud forecasts over global scales are still lacking.

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This study is therefore carried out with the aim of assessing the cloud-forecast ability of a global numerical model to provide insight into its reliability as a reference for astronomical observations. In order to do this, we need (i) the output from a global numerical model as forecast data and (ii) observational data with appreciable temporal and spatial coverage. The selection and reduction of such data will be discussed in the following section.

2 DATA SELECTION AND PREPARATION

2.1 Modelling data

The ECMWF and GFS models mentioned in Section 1 are among the major global numerical weather models used for daily weather forecasts. In this study, we follow our earlier study and use the GFS model as well. First, we retrieved the GFS data in grid 003 (1° × 1° grid) for the period of 2005 July–2008 June from the National Operational Model Archive & Distribution System (NOMADS: see Rutledge, Alpert & Ebisuzaki 2006). The data are at three-hourly intervals for forecast lead time (τ) up to 180 h and are produced four times per day at 00Z (where Z denotes Universal Time (UT)), 06Z, 12Z and 18Z (we refer to each of them as one ‘initialization’ hereafter). The data are then weight-averaged into the spatial resolution of 2.5° to match the definition of the observational data to be described in Section 2.2.

The forecast cloud fraction in decimals, C, is computed using the Xu–Randall cloud scheme (Xu & Randall 1996):

\[ C = RH^{k_1} \times \left\{ 1 - \exp \left[ - \frac{k_2 q_l}{((1 - RH) q_l)_{0.25}} \right] \right\}, \]

where RH is the environmental relative humidity, q_l is the liquid water mixing ratio, q_s is the saturation specific humidity and k_1 = 0.25, k_2 = 100 and k_3 = 0.49 are empirical coefficients. q_s is calculated with respect to water phase or ice phase and environmental temperature.

We will deal with five types of cloud cover in this study: total cloud cover, which accounts for cloud cover over the entire atmospheric column and is most closely related to observational astronomy, layer cloud cover (low, mid and high level), which divides according to the cloud-top pressure (680 hPa, 440 hPa and <440 hPa) and is particularly useful for observatories that are mainly affected by a certain cloud type (e.g. high cloud for high-altitude observatories), and convective cloud, which is mostly associated with convective weather that can be an unwarned-of threat for astronomical observations.

The GFS model divides the whole atmospheric column into 64 sublayers for simulation and cloud cover is derived under the assumption that clouds in all sublayers for the corresponding layer are maximally randomly overlapped (Yang et al. 2006). The exception is convective cloud, which is derived based on the method proposed by Pan & Wu (1995).

2.2 Observational data

Rather than using ‘traditional’ surface observations, we decided to use calibrated satellite observations in this study. The reason is that standard cloud observations are not practised by a number of surface meteorological stations, as such observations need to be carried out by expert observers, and therefore qualified observations are mostly limited to inhabited areas with dense populations, which are avoided by most astronomical observatories. Satellite observations, on the other hand, have better temporal and spatial coverage. Since they are carried out by robotic observers and reduced following identical algorithms, it is also easier to determine the scale of uncertainty.

A good source of such data is the International Satellite Cloud Climatology Project (ISCCP; cf. Schiffer & Rossow 1983; Rossow & Schiffer 1999), which we will use for our study.

We retrieve three-hourly ISCCP D1 data from the ISCCP data base for the same time period as the GFS data. The D1 data set has a spatial resolution of 280 km and includes cloud cover data for total, low, mid and high cloud as well as convective cloud. The data are determined from raw satellite observations of cloud-top pressure and optical thickness and have the same definition as the GFS data that we used. We then transform the ISCCP data from an equal-area grid on to an equal-angle grid following the method of Rossow et al. (1991), to match the projection set-up of the GFS data.

The uncertainty in the ISCCP data is estimated to be ~0.15 for individual cases and less than ~0.05 for 30-day means (Schiffer & Rossow 1983; Rossow & Schiffer 1999). However, additional studies did reveal some observational tendencies for each cloud type.

(i) Rossow, Walker & Garder (1993, surface observations): ISCCP is 0.10 too low over land (less in summer and more in winter).

(ii) Rossow et al. (1993) and Hahn, Warren & London (1995) (surface observations): ISCCP misses some (up to 5 per cent) clouds at night.

(iii) Rossow & Schiffer (1999, Stratospheric Aerosol and Gas Experiments, High-Resolution Infrared Sounder and surface observations): ISCCP high clouds are at least 0.05–0.10 too low.

(iv) Curry & Ebert (1992) and Rossow et al. (1993) (surface and satellite observations): ISCCP total clouds for polar regions are 0.15–0.25 too low in summer and 0.05–0.10 too high in winter.

(v) Wielicki & Parker (1992, satellite observations): overall tendencies of ISCCP low clouds are less than 0.1.

As noted by Curry & Ebert (1992) and Rossow et al. (1993), the ISCCP observations over the polar regions suffered from strong seasonal tendencies due to low visual and thermal contrast between the surface and clouds; therefore, we will focus on the region between 60° S and 60° N in our study, despite still including results from the polar regions in our figures.

3 EVALUATION AND RESULTS

3.1 Evaluation methodology

We generate over 1 million GFS–ISCCP data pairs of every initialization, forecast time point and cloud type for the entire time period of interest. To obtain a more objective evaluation of the model forecast skill for total cloud cover, we compose three additional models that are to be compared with the ISCCP data.

(i) Climatological model, created by averaging ISCCP cloud data from 2004 July–2005 June. This model will be used to assess whether the GFS model is more skilled than the statistical climatology forecast.

(ii) Randomize model, which creates random series of pseudo-global cloud fields under a uniform distribution. This model will be used to assess whether the GFS model is more skilled than unskilled guesses.

(iii) Persistence model, which fixes the observation at τ = 0 h for a given initialization throughout the forecast period. This model will be used to compare the GFS model against a persistent ‘guess’.
Limited by computational resources, we randomly chose 2006 July for such comparisons. We will show that monthly variation of forecast error is not significant in the period of study, so the 2006 July result is representative.

We use a different evaluation scheme for convective cloud. Although we are dealing with the term ‘convective cloud cover’ or ‘fractional convective cloud’, there is virtually no scientific/observational meaning to this term. This is due to the small scales of most convective clouds compared with the spatial resolution of a global model or satellite camera (mostly tens of km), so that such cloud can only be represented by fractional numbers in model outputs or observations. Therefore, in addition to fractional comparisons, we also ‘binary degenerate’ the modelling and observational data, so that binary statistical indicators can be used to assess the forecast skill (see Section 3.4.2).

### 3.2 Total cloud

#### 3.2.1 General forecast accuracy

Fig. 1 shows the three-year mean of forecast minus observation (abbreviated as $fc - obs$ below) of total cloud cover forecast at $\tau = 3\text{h}$ at 12Z initialization; we notice that the $fc - obs$ set-ups for other time points are more or less the same and do not include them in the paper. Fig. 2 shows the three-year global mean (excluding polar regions) probability with <30 per cent forecast error throughout the forecast period ($\tau$ from 0h to 180 h) at 12Z initialization. Although the root-mean-square error (RMSE) is commonly used in prediction evaluation, we notice that the preliminary RMSE behaves almost the same as the tendency (Fig. 1), which suggests that the main contribution of forecast RMSE is to persistent regional tendency rather than dispersion. Therefore, we argue that the RMSE distribution and variation are representable using Figs 1 and 2.

![Figure 1](image.png)

**Figure 1.** The three-year mean of forecast minus observation ($fc - obs$) distribution for total cloud cover forecast at $\tau = 3\text{h}$ at 12Z initialization. Regions with $fc - obs$ beyond ±15 per cent are shaded in colour.

![Figure 2](image.png)

**Figure 2.** The three-year global mean (excluding polar regions) probability with <30 per cent forecast error for $\tau = 0 - 180\text{h}$ at 12Z initialization for total cloud cover forecast. Error bars represent standard variation.

### 3.2.2 Daily and seasonal variation

Since most astronomical optical observations are conducted during the night hours, we are interested in examining the daily variation of forecast accuracy. We divide the entire globe into 24 time zones with equal longitudinal spacing, and average the $fc - obs$ series with respect to the local hour in each time zone. As illustrated in Fig. 3, the daily $fc - obs$ value varies between −15 per cent and −5 per cent for the entire globe (excluding the polar regions) and ocean, but for land it varies from −13 per cent in the morning to +5 to +10 per cent during the night hours. However, considering a ~7 per cent underestimation of ISCCP data over land during the day and ~12 per cent underestimation during the night (Rossow et al. 1993), the actual $fc - obs$ could be as low as −25 per cent during the day but near 0 per cent at night.

![Figure 3](image.png)

**Table 1.** Statistics of three-year mean $fc - obs$ for total cloud cover forecast at 12Z initialization.

| Region               | $\tau$ | Mean $fc - obs$ |
|----------------------|--------|-----------------|
| Land                 | 3h     | 0.28 per cent   |
|                      | 180h   | 0.25 per cent   |
| Ocean                | 3h     | −10.31 per cent |
|                      | 180h   | −11.28 per cent |
| Northern hemisphere  | 3h     | −5.85 per cent  |
|                      | 180h   | −6.34 per cent  |
| Southern hemisphere  | 3h     | −9.11 per cent  |
|                      | 180h   | −9.91 per cent  |

In Tables 1 and 2, our analysis shows that the global mean $fc - obs$ (excluding polar regions) varies from −6.43 per cent to −8.93 per cent depending on initialization. Negative values are mostly contributed by low $fc - obs$ values over ocean, especially in western coastal regions at mid-latitude. The forecast over land matches the observation well (between −0.5 per cent and +1 per cent throughout the forecast period), but it may be positively biased according to the suggested underestimation of ISCCP data over land by Rossow et al. (1993). Meanwhile, the difference between each initialization is not significant compared with the $fc - obs$ tendency (only ~3 per cent or less). We also find that the negative tendency over the southern hemisphere is stronger than that of the northern hemisphere.

Fig. 2 shows that the probability of <30 per cent forecast error gradually decays from ~73 per cent at $\tau = 3\text{h}$ to ~58 per cent at $\tau = 180\text{h}$. One may argue that ±30 per cent has covered three-fifths of the possible range (0–100 per cent), which may lift the probability; however, cloud cover is not uniformly distributed: on a significant number of occasions, the cloud cover is close to either 0 per cent or 100 per cent, so ±30 per cent is a fairly reasonable constraint. We will also show that the GFS model is solidly better than the random-guess model in a later section.
How good is the cloud cover forecast?

3.2.3 Comparison with climatology, randomize and persistence models

As described before, we generated three additional models and will compare them with the ISCCP data for 2006 July. The result is shown in Fig. 6 and, in our opinion, is comparable with Fig. 2 despite the different temporal coverage, as we have shown the seasonal variation to be insignificant compared with the overall \( fc - obs \) tendency.

We can see the GFS model is superior to all three other models at most time points. Statistically, the persistence model is best of all for \( \tau < 6 \) h, but this is not meaningful as the GFS model data are not available after approximately 4–5 h of the respective initialization time due to computational layover. We note that the ISCCP climatology model becomes better than the GFS model after \( \tau \sim 120 \) h and that both models are more skilled than a random guess at all times. From this result, we can conclude that the GFS model is skilled and performs better than the ISCCP climatology model until \( \tau \sim 120 \) h.

### Table 3. Statistics of three-year mean \( fc - obs \) for low, mid and high cloud at 12Z initialization.

| Cloud type  | Region       | Three-year mean \( fc - obs \) |
|-------------|--------------|---------------------------------|
| Low cloud   | 60° S to 60° N | +3.08 per cent                  |
|             | 0° to 60° N   | +1.60 per cent                  |
|             | Low          | +4.35 per cent                  |
|             | Land         | +7.05 per cent                  |
|             | Ocean        | +1.82 per cent                  |
| Mid cloud   | 60° S to 60° N | −1.21 per cent                  |
|             | 0° to 60° N   | −0.59 per cent                  |
|             | Low          | −1.80 per cent                  |
|             | Land         | +1.63 per cent                  |
|             | Ocean        | +1.60 per cent                  |
| High cloud  | 60° S to 60° N | +17.11 per cent                 |
|             | 0° to 60° N   | +18.79 per cent                 |
|             | Low          | +15.67 per cent                 |
|             | Land         | +15.92 per cent                 |
|             | Ocean        | +16.85 per cent                 |
Figure 7. The three-year mean $f_c - obs$ distribution for low, mid and high cloud cover forecast at $\tau = 3$ h at 12Z initialization. Regions with $f_c - obs$ beyond $\pm 15$ per cent are shaded in colour.

Figure 8. The three-year global mean (excluding polar regions) probability variation with $< 30$ per cent forecast error for $\tau = 0$–180 h for low, mid and high cloud cover forecast at 12Z initialization. Error bars represent standard deviation.

Figure 9. The three-year mean zonal $f_c - obs$ for low, mid and high cloud at 12Z initialization.

Table 4. Statistics of three-year mean $f_c - obs$ for convective cloud at 12Z initialization.

| Region           | $\tau$ | Three-year mean $f_c - obs$ |
|------------------|--------|-----------------------------|
| Land             | 3h     | $-5.11$ per cent            |
|                  | 180h   | $-5.08$ per cent            |
| Ocean            | 3h     | $-3.39$ per cent            |
|                  | 180h   | $-4.37$ per cent            |
| Northern hemisphere | 3h    | $-3.67$ per cent            |
|                  | 180h   | $-4.41$ per cent            |
| Southern hemisphere | 3h    | $-3.65$ per cent            |
|                  | 180h   | $-4.88$ per cent            |

data (Rossow & Schiffer 1999) and is questionable. We can also identify an underestimation of low cloud off the west coast of major continents at mid-latitude, which seems to be the major contribution to the underestimation of the total cloud in these regions. At high latitude, the model tends to overestimate the low cloud.

The probability of $<30$ per cent error forecast for low cloud is significantly lower than that for the other two types of cloud (Fig. 8), but it does not appear to affect the total cloud at small $\tau$. This behaviour, together with the unexpected negative $f_c - obs$ for total cloud (while $f_c - obs$ values for layer clouds are mostly positive), could indicate that the assumption of maximally random overlaps (see Section 2.1) between cloud layers may not apply at all times.

3.4 Convective cloud

3.4.1 Fractional evaluation

Direct fractional comparison (Table 4 and Fig. 10) shows that model overestimation only occurs in tropical areas (within 15° latitude in both hemispheres), while moderate to strong underestimation (mostly 10–20 per cent) occurs in mid-to-high latitude areas.
Considering the fact that convective weather is frequent in tropical areas throughout the year but is relatively rare in mid-to-high latitude areas, we may conclude that the current model misses and/or underestimates a significant fraction of convective cloud in mid-to-high latitude areas, while it tends to overestimate the amount and/or intensity of convective cloud in tropical areas.

### 3.4.2 Binary evaluation

An alternative way to evaluate the GFS convective cloud forecast is to degenerate the forecast and observation into a binary value, so we can focus on the occurrence of such cloud rather than a mixture of occurrence and intensity. As discussed in earlier sections, we set a cut-off limit of 1 per cent for convective cloud fraction to put both modelling and observational data into the categories of ‘convective cloud’ and ‘no convective cloud’. We use the following statistical indicators for evaluation: Proportion of Perfect Forecasts (PPF), Probability of Detection (POD), False Alarm Rate (FAR) and Frequency Bias Index (FBI). In the following expressions, \( H \) indicates ‘hits’ (forecast and observed), \( F \) indicates ‘false alarms’ (forecast but not observed), \( M \) indicates ‘missed’ (not forecast but observed) and \( Z \) indicates not-forecast and not-observed events. The result is shown in Fig. 11.

\[
\text{PPF} = \frac{H + Z}{H + F + M + Z},
\]

\[
\text{POD} = \frac{H}{H + M},
\]

\[
\text{FAR} = \frac{F}{F + Z}.
\]

**Figure 11.** The global mean variations (polar regions excluded) of four statistical indicators for convective cloud forecast at 12Z initialization throughout the forecast period.

As we have shown that tropical overestimation comprised only a relatively small fraction of the sample, the set-up of Fig. 11 more or less represents the situation for mid-to-high latitude areas. This is affirmed by the FBI value, which lies way below 1, suggesting a global underestimation of convective cloud.

The PPF varies around 0.6 and creates a decent picture of the forecast ability, but the rare occurrence of convective cloud in most areas will lead to a significant fraction of PPF being contributed by ‘Z’ events (not-forecast and not-observed), so we must take POD and FAR into account for an unbiased view. From POD we notice that only slightly less than half of the convective cloud can be detected by the model. Since convective cloud is most commonly seen in tropical areas, the POD for mid-to-high latitude areas must be lower. However, globally speaking, the model is still very skilled as the FAR is about twice as low as the POD.

### 4 CONCLUDING REMARKS

To study the reliability of cloud forecasts from the GFS model as a reference for astronomical observations, we analysed a three-year sample composed of GFS modelling data and satellite observation data from ISCCP. The results are summarized as follows.

(i) For total cloud cover forecast, there is a slight global underestimation from the GFS model, but this is more or less within the observational uncertainty of the ISCCP data. For local night hours, the model forecast roughly agrees with the observation if the observational tendency of ISCCP data is taken into account, as suggested by earlier studies. The global mean probability (excluding polar regions) of <30 per cent forecast error gradually declines from 73 per cent to 58 per cent from \( \tau = 3 \) h to \( \tau = 180 \) h. Further investigation suggests that the climatology model based on ISCCP observations overtakes the GFS model after \( \tau \sim 120 \) h, but both models are significantly more skilled than random guesses.

(ii) We found a strong underestimation of low clouds in subtropical regions off the west coast in both hemispheres. Overestimation of low clouds in high-latitude areas can also be identified. We found some 15 per cent global overestimation of high clouds, but this is most likely compromised by a similar scale of observational tendency in the ISCCP data. We noted the inconsistency in mean global forecast errors between total and layer clouds, which might be due to the layer-overlapping assumption built into the model.

(iii) For convective cloud forecast, the GFS model tends to underestimate the occurrence and/or intensity of convective cloud in tropical areas but tends to underestimate that in subtropical and high-latitude areas. We found that the GFS model can identify less than half of the convective cloud globally. However, the convective cloud forecast is still skilled, as the detection rate is about twice as high as the false-alarm rate, leading to a proportion of perfect forecasts of ~0.6.

In all, we observed a good overall consistency between the GFS model forecast and ISCCP observations throughout the time period of interest. For total cloud cover, our result suggested a satisfactory performance of the GFS model for the requirements of observation scheduling up to a week ahead. However, for layer and convective cloud, which can be considerably important for observatories located in certain environments (for example, high cloud
for high-altitude observatories), the success rate of the GFS model is relatively less satisfying than that of the total cloud forecast.

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