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Fog forecasting: "old fashioned" semi-empirical methods from radio sounding observations versus "modern" numerical models

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Abstract

Despite the recently improved skill of numerical weather prediction (NWP) models, fog remains difficult to forecast. Hence, we examine whether empirical methods as developed in the 60s&70s are reasonable alternatives forecast tools. It appears that the so-called Fog Stability Index (FSI), solely based on routine radio sounding observations, has reasonable skill. Also, the FSI has been optimized for 12 stations in the Netherlands, after which FSI reaches a high forecast skill. It appears this skill approaches the skill of direct MM5 model output.

1. Introduction

Recent decades resulted in improved skill of high-resolution NWP models. Unfortunately, fog remains difficult to forecast due to the fog's local nature limited vertical and horizontal model resolution, relatively poor knowledge on the relevant processes, on small (radiation, turbulence, aerosols) and on larger scales (advection, subsidence; [1,2,4,8]).

Despite these difficulties, it is imperative to improve fog forecast since fog cause adverse effects in air- and sea traffic [6], leaf wetness duration, asthma when fog coincides with industrial pollution [5].

The apparent difficulties of NWP-models motivate us to evaluate the skill of empirical methods developed in the 60s&70s. The FSI is an empirical method, developed by the US Air Force [3]. Its simplicity is its main advantage: it requires only four variables that are directly available from radiosonde observations. The FSI is defined as:

$$\mathbf{FSI = 2.(\mathit{T}\text{-}\mathit{T}_d) + 2.(\mathit{T}-\mathit{T}_{850}) + \mathit{W}_{850}} \quad \mathbf{(1)}$$

With T and T_d the temperature (ºC) and dew point at 2m (ºC), T_{850} and W_{850} are the temperature (ºC) and wind speed at 850 hPa respectively (i.e. outside the planetary boundary layer). The three terms in (1) represent humidity (T-T_d), stability (T-T_{850}) and wind speed (W_{850}). FSI< 31 indicates a high probability of fog formation, 31<FSI<55 implies moderate risk of fog, and FSI>55 suggests low fog risk. Unfortunately, the forecast's lead time is unclear. Fog formation is favored for high humidity (T-T_d small), the atmosphere is stable (weak mixing, T-T_{850} is small) and low wind speed (no mixing, W_{850} is small). The aims of this study are:

-To evaluate FSI against routine observations.
-To compare skill of FSI with the skill of the forecasts with the mesoscale model MM5.
-To optimize FSI for the Netherlands.

2. Methodology

2.1 Evaluation at Cabauw

First, the FSI skill for a 6h forecast is evaluated against fog observations at Cabauw (Netherlands), where a present weather sensor observes obstruction near the ground, i.e. fog. The dataset covers 01-02-2006 until 31-12-2008, of 10 min averaged visibility measurements. Input for the FSI originates from the radio sounding in De Bilt (52º11'N; 05º11'E).

In order to evaluate the FSI skill, a number of skill scores based on a contingency table have been used [10]. Fog is rare, and it is likely that by far most of the situations result in a correct no-fog forecast. These situations are less interesting since we aim to correctly forecast fog, not focus on no-fog situations. The skill score to asses FSI skill, i.e. the Critical Success Index (CSI), not dependent on the correct no-fog forecasts. CSI is the fraction of correct fog forecast of the total amount of interesting situation (both correct fog forecasts and all wrong forecasts). Ideally, the CSI=1 (all forecasts correct) and in case fog is never correctly forecasted CSI=0. Note that for rare events it is more difficult to obtain high CSI values [10]. Furthermore, note that similar conclusions were drawn based on other skill scores, as the Hansen-Kuipers score and the Extreme dependency score (not shown). Alternatively, the Hit Rate (HR) and False Alarm Ratio (FAR) indicate which part of the *fog events* is correctly forecasted, and which part of the *fog forecasts* is incorrect respectively. A combined measure based on CSI, HR and FAR would be ideal.

2.2 Evaluation for 12 sites

The analysis from §2.1 has been extended for 12 AWS stations, for the period 01-01-2004 until 31-08-2009. For the FSI, the humidity term (T-T_d) has been determined from local observations, while the stability, and wind speed, were recorded from the radio sounding.

To optimize FSI, the data were split in two parts. The first part, from 01-01-2004 until 31-12-2005, was used to determine the exact values of new coefficients. The second part, from 01-01-2006 until 31-08-2009, was used for validation purposes. We use a Monte-Carlo approach in which the coefficients in Eq. (2) below are varied, as well as is the threshold value for the FSI. To avoid effects of fog being present at the forecast time, the forecast lead time in the optimalization is 2-6 hours. Note the current threshold for high fog risk is FSI<31, but this has never been validated for the Netherlands.

$$\mathbf{FSI} = \boldsymbol{a}.(\boldsymbol{T}\text{-}\boldsymbol{T}_{\mathbf{d}}) + \boldsymbol{b}.(\boldsymbol{T}-\boldsymbol{T}_{\mathbf{850}}) + \boldsymbol{c}.\boldsymbol{W}_{\mathbf{850}} \qquad \mathbf{(2)}$$

Alternatively, we enter the 10m wind speed as an additional predictor:

$$\mathbf{FSI} = \boldsymbol{a}.(\boldsymbol{T}\text{-}\boldsymbol{T}_{\mathbf{d}}) + \boldsymbol{b}.(\boldsymbol{T}-\boldsymbol{T}_{\mathbf{850}}) + \boldsymbol{c}.\boldsymbol{W}_{\mathbf{850}} + \boldsymbol{d}.\boldsymbol{W}_{\mathbf{10}} \qquad \mathbf{(3)}$$

The relative impact of each term (3) is denoted by the coefficients *a*-*b*-*c*. Originally, *a*-*b*-*c* is 2-2-1. It is likely that a small fluctuation in the humidity term (e.g. 0.3K) might be more important for fog forecasting than a small fluctuation in the 850 hPa wind speed (0.6 ms^{-1}).

2.3 Benchmark with MM5

The FSI results on basis of the observations is compared with forecasts by MM5, The latter is a mesoscale model operationally run at Wageningen University for 48 h forecasts [7], using the MRF-PBL scheme, the NOAH land surface scheme in the evaluated set-up, using a 9 km resolution and GFS boundary conditions. Output for temperature, relative humidity, and wind speed have been used to deduced whether fog was forecasted with a lead time of 6 h [11].

3. Results

3.1 Results for Cabauw

Fig. 1 shows that the FSI with original threshold, reaches a CSI=0.38. This is surprisingly high since [9] reports a CSI = 0.35 for a complete NWP model including post-processing by model output statistics. Direct model output from MM5 provides CSI=0.22, and as such FSI seems to outperform MM5. Fig. 1 also shows that FSI skill depends on the selected threshold. Although both HR and FAR increase for larger threshold values, CSI is optimum of ~30, and as such appears to be optimizable.

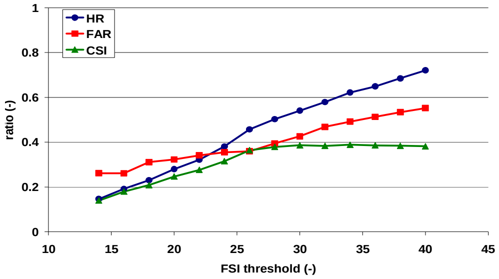

Fig. 1: Skill score for FSI, varying threshold value

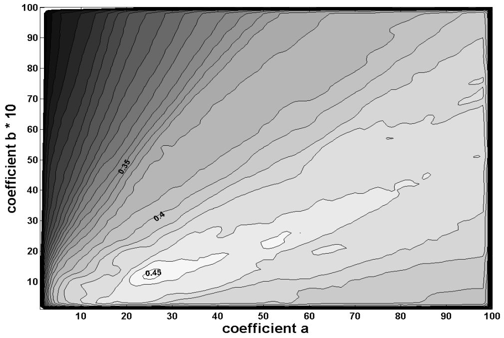

Fig 2: Contour plot of CSI a domain of for a and b, for Lelystad.

3.2 Wider verification and optimalization.

Verification on a broader dataset (see Appendix) shows FSI scores worse than for Cabauw (median CSI=0.23, Fig. 3), which might be due to the fact that Cabauw is an ideal site for fog formation (flat, humid soil), and the sounding that feeds FSI is taken relatively close to Cabauw.

For the optimalization, detailed analysis is shown for Lelystad. §3.1 indicated modifying threshold values will likely benefit the quality of fog forecasting, the threshold values have again been modified.

For Lelystad CSI improves from 0.19 to 0.22 for adjusted threshold values. Apparently the threshold optimalization lacks the desired effect, seems to result in a worse skill since HR decrease a lot more than FAR. However, these scores are ratios and a closer look at the absolute values indicates one obtains indeed less wrong forecasts.

Subsequently, we optimize the ratio *a*-*b*-*c*. For each set of coefficients, an optimum threshold value has been determined, and the corresponding CSI values are plotted (Fig. 2). Apparently, the FSI skill would benefit a lot from modified coefficients. For Lelystad $a \cong 25$ and $b \cong 1.5$. The modified coefficients resulted in a better CSI score in the validation stage. Again HR decreased, but FAR decreased slightly more, which net resulted in a reduced amount of wrong forecasts compared to the original FSI.

Finally we analyze Eq. (3) with W_{10} included as predictor. For Lelystad the best results where found for $d = 6$, while *a* and *b* slightly changed to values 20 and 0.5. Although CSI decreases only slightly from the previous modification, HR and FAR both increased. Apparently more fog events are correctly forecasted, but there are also more false fog forecasts. It is questionable whether this is desirable or not.

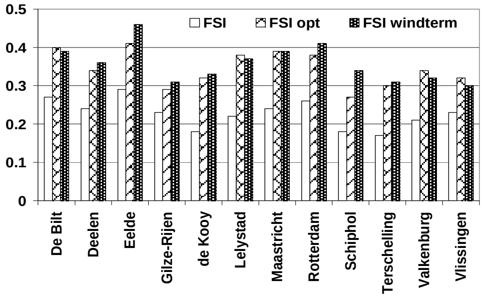

Fig 3: CSI for the validation of recalibrated FSI.

The original FSI has some potential, but the optimalization clearly made the difference, resulting in a large improvement of the skill. Whether or not the addition of W_{10} has any use is debatable, since CSI does not increase for all stations.

The original FSI formula, with optimized threshold values but with original coefficients, also has lower CSI scores compared to the Cabauw study. The CSI has a maximum of 0.29 for Eelde, and a minimum value of 0.17 for Terschelling. The modifications are beneficial for all stations, though the additional W_{10} does not provide skill improvement for all sites. Without $W_{10,}$ the CSI score vary between 0.41 (Eelde) and 0.27 (Schiphol). Including W_{10} leads on average to slight improvements. The maximum CSI value is 0.46 (Eelde) and the minimum CSI= 0.3 (Vlissingen). HR and FAR of the optimized FSI indicate the main advantage of $W_{10}$is, in general, a higher HR. Overall ~65% of all fog events are also correctly forecasted, compared to 59% if W_{10} is excluded. Unfortunately, also FAR rises slightly (53% -> 56%).

The site specific optimalizations as applied here have a side effect that a generally valid FSI formula is missing. In order to summarize our results, the mean ratio of *a/b* appears to be 0.09, which results in a=21 and b= 2 (Fig. 4). Hence a general FSI formula would be:

$$\mathbf{FSI = 21.(}\boldsymbol{T}\text{-}\boldsymbol{T}_{\mathbf{d}}\mathbf{) + 2.(}\boldsymbol{T}-\boldsymbol{T}_{\mathbf{850}}\mathbf{) + 0.5.}\boldsymbol{W}_{\mathbf{850}} \qquad \mathbf{(4)}$$

The corresponding threshold value where fog is forecasted fog is found by applying this relation in the validation dataset of each station. The optimal threshold value is on average 26, varying between 22 and 30, and the corresponding CSI value is on average 0.35, varying between 0.41 and 0.28. CSI values for the threshold of 26 would be slightly lower.

For the optimized FSI, the mean CSI is 0.35. This means that for every correct fog forecast two incorrect forecasts are made. This appears to be quite inaccurate, but it has to be noted that the CSI is dependant on the observed percentage of fog events as mentioned in § 2.1. The observed fog frequency for these stations varies between 2.8% (Vlissingen) and 8.9% (Deelen). It appears that the accuracy, defined as the amount of total correct forecasts divided by the total amount of forecasts, in all situations is higher than 90%, with a maximum of 97% for observation station Vlissingen. Apparently, even though the FSI is a simplified empirical relationship, it is capable of high accuracy forecasting. Overall, ~95% of all forecasts are correct, either correct fog forecasts or correct no-fog forecasts.

Conclusions

This paper examines the skill of a modern numerical weather predication model MM5, relative to simple empirical methods based on sounding observations (FSI). It appears that FSI scores better than direct model output from MM5, and performs reasonable once optimized for site specific conditions.

Acknowledgements

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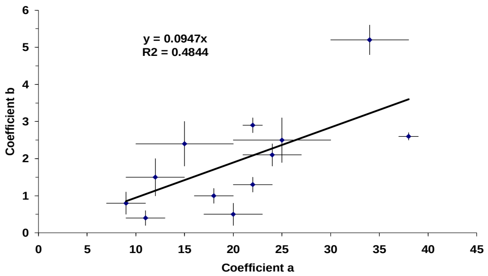

Fig. 4: Relation between coefficient a and b for Equation 2.

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Appendix:

Fig. A1: Observation sites in The Netherlands