Article ID: 1006-8775(2016) 01-0066-08

IMPROVEMENT OF REGIONAL PREDICTION OF SEA FOG ON GUANGDONG COASTLAND USING THE FACTOR OF TEMPERATURE DIFFERENCE IN THE NEAR-SURFACE LAYER

HUANG Hui-jun (黄辉军), HUANG Jian (黄 健), LIU Chun-xia (刘春霞), MAO Wei-kang (毛伟康), BI Xue-yan (毕雪岩)

(Guangdong Provincial Key Laboratory of Regional Numerical Weather Prediction and Joint Open Laboratory of Marine Meteorology, Guangzhou Institute of Tropical and Marine Meteorology, CMA, Guangzhou 510080 China)

Abstract: The relationship between the factor of temperature difference of the near-surface layer ($T_{1\,000\,hPa}$-$T_{2\,m}$) and sea fog is analyzed using the NCEP reanalysis with a horizontal resolution of 1°×1° (2000 to 2011) and the station observations (2010 to 2011). The element is treated as the prediction variable factor in the GRAPES model and used to improve the regional prediction of sea fog on Guangdong coastland. (1) The relationship between this factor and the occurrence of sea fog is explicit: When the sea fog happens, the value of this factor is always large in some specific periods, and the negative value of this factor decreases significantly or turns positive, suggesting the enhancement of warm and moist advection of air flow near the surface, which favors the development of sea fog. (2) The transportation of warm and moist advection over Guangdong coastland is featured by some stages and the jumping among these states. It also gets stronger over time. Meanwhile, the northward propagation of warm and moist advection is quite consistent with the northward advancing of sea fog from south to north along the coastland of China. (3) The GRAPES model can well simulate and realize the factor of near-surface temperature difference. Besides, the accuracy of regional prediction of marine fog, the relevant threat score and Heidke skill score are all improved when the factor is involved.

Key words: weather prediction; regional prediction of marine fog; Guangdong coastland; GRAPES model; factor of near-surface temperature difference

CLC number: P436.4 **Document code:** A

doi: 10.16555/j.1006-8775.2016.01.008

1 INTRODUCTION

Although there have been much investigation and research in the past, the prediction of sea fog is still a complex and challenging problem (Zhou [1]; Leipper[2]; Lewis et al.[3]). Early prediction of sea fog is based on the analysis of weather maps, the experience of forecasters (Willett[4]; Douglas[5]; Petterssen[6]; Leipper[7]) and the dynamical statistical analysis on the model results, including the artificial intelligence (Peak and Tag[8]; Tag and Peak [9]) and the model output statistic (MOS) (Koziara et al.[10]; Hu et al.[11]). Recently the application of numerical model on the fog prediction has increased gradually. The primary models used to predict the fog include the 1-D model (Bergot[12]; Rémy and Bergot[13]), 3-D model (Yang[14]) and the atmosphere-ocean coupling model (Heo and Ha [15]), and so on. The fog prediction has been improved by these models.

The advection-cooling fog, which appears all over the world as a primary kind of marine fog, is the major category of sea fog along the Chinese coast (Lewis et al.[3]; Wang [16]; Gultepe et al.[17]). The advection-cooling fog is formed by the advection of warm air onto the cold sea surface, featured by thermal inversion or the presence of an isothermal layer near the sea surface. The turbulence relevant to the wind shear transports the heat energy to the sea surface (Taylor[18]; Rodhe[19]; Pilié[20]). The inland observation on sea fog in Qingdao conducted in the 1950s found out that a low-level thermal inversion or isothermal structure exists in the advection-cooling fog[16]. Recently Zhang et al.[21]. and Ren and Zhang[22] used the data observed by inshore buoys and a L-waveband wind-detecting radar to confirm the thermal inversion and isothermal structure in the boundary layer of advection-cooling fog over the Yellow Sea in spring and summer. Gao et al.[23] simulated the thermal inversion on the lower layer of advection-cooling fog over the Yellow Sea by the MM5 model. The sea fog over the South China Sea usually appeared offshore. Recent researches suggested that the sea fog on the

Received 2014-04-04; **Revised** 2015-10-20; **Accepted** 2016-01-15

Foundation item: Chinese Special Scientific Research Project for Public Interest (GYHY200906008); Natural Science Foundation of China (41275025); Guangdong Science and Technology Plan Project (2012A061400012); Meteorological Project from Guangdong Meteorological Bureau (201003); Research on Pre-warning and Forecasting Techniques for Marine Meteorology from Guangdong Meteorological Bureau

Biography: HUANG Hui-jun, Ph.D., associate researcher, primarily undertaking research on air-sea boundary layer and marine meteorology

Corresponding author: HUANG Hui-jun, e-mail: hjhuang@grmc.gov.cn

South China coast in winter and spring is mostly the advection-cooling fog, especially the heavy fog lasting more than 1 day (Huang et al.[24]; Huang et al.[25]). Huang et al. investigated the observation dataset of sea fog on the South China coast and put forward a schematic diagram of advection-cooling fog and clarified the existence of a near-surface thermal inversion layer in the sea fog on the South China coast under the influence of warm and moist advection[24]. Furthermore, Huang et al. studied the structure of the boundary layer of sea fog on the South China coast and proposed a close association between the near-surface thermal inversion and the marine fog[25]. They also defined the height of zero vertical gradient of pseudo-equivalent potential temperature ($\partial\theta_{se}/\partial z$=0) as the height of thermal turbulence interface in the marine fog, which was considered as the important turbulence interface in the occurrence and development of marine fog. It was also the major reason for the maintenance of sea fog and stratus cloud. Therefore, the key characteristics of advection-cooling fog are the existence of thermal inversion or isothermal structure near the surface.

Huang et al.[26] inspected the NCEP reanalysis data and station observations to study the 24 to 48 h regional prediction of sea fog on the Guangdong coast by utilizing the output of GRAPES meso-scale regional model developed by the Guangzhou Institute of Tropical and Marine Meteorology, China Meteorology Administration (CMA). They examined many prediction factors, such as the lower wind direction and speed, the lower warm and moist advection, the basic elements in the lower troposphere, the vorticity and divergence, etc. In the vertical structure of air temperature, they used the temperature difference between 925 hPa and 1 000 hPa to represent the thermal structure above the surface layer in the marine fog. Such factor has been proved to be one of the valid prediction variable factors. This paper aims at establishing a new factor of near-surface temperature difference, i.e., the difference of temperature between 1 000 hPa and 2-m height ($T_{1\,000\,\text{hPa}}-T_{2\,\text{m}}$), to represent the thermal feature near the surface during the marine fog. Then we will try to improve the prediction of sea fog on the Guangdong coast by involving the new factor.

In this work, the NCEP reanalysis and station observational datasets are first used to reveal the effectiveness of near-surface temperature difference, and then the concrete value of this factor studied before being realized in the GRAPES model. In the last stage, the 24-h regional prediction of sea fog on the Guangdong coast is compared and tested with and without such factor. Section 2 introduces the dataset. The relationship between the near-surface temperature difference and the occurrence of sea fog is analyzed in Section 3. Section 4 presents the process by which the prediction variable factor is realized in GRAPES model. And the prediction results are partly tested in Section 5. The conclusions and discussion are arranged in Section 6.

2 DATA DESCRIPTION

The meteorological elements are extracted from the 6-hourly NCEP reanalysis dataset with a horizontal resolution of 1°×1°. The records are downloaded from http://dss.ucar.edu/datasets/ds083.2. The sea fog observations on the Guangdong coast are supplied by the Guangdong Climate Center.

The model results applied to the regional prediction of sea fog on the Guangdong coast are obtained from the meteorological products output by the GRAPES meso-scale regional model with a horizontal resolution of 0.12°×0.12° and a vertical resolution of 17 levels. The GRAPES meso-scale regional model, which is developed and maintained by a specific science group for a long time, has been run in practice (Ding et al.[27]; Chen et al.[28]).

3 RELATIONSHIPS BETWEEN THE NEAR-SURFACE TEMPERATURE DIFFERENCE AND THE OCCURRENCE OF MARINE FOG

The sea fog occurs more frequently in 2010 than in 2011 on the Guangdong coast. To understand the relationship between the near-surface temperature difference and the occurrence of sea fog, we analyze the regional prediction of sea fog in five specific sites of Zhanjiang, Yangjiang, Zhuhai, Shanwei and Shantou for 2010 and 2011, respectively (Fig.1). The formula $T_{1\,000\,\text{hPa}}-T_{2\,\text{m}}$ is applied to calculate the near-surface temperature difference using the NCEP reanalysis data at 00 UTC (0800 local time) over the oceanic area in the vicinity of the specific sites. The index of marine fog occurrence is identified by station observations. Specifically, the index is 1 when the sea fog is observed and it is 0 when no sea fog takes place. Fig.1 shows that the near-surface temperature difference is large when sea fog happens. In the meantime, negative near-surface temperature difference decreases significantly or even turns positive, indicating the warming of near-surface air which is attributed to the enhancement of warm and wet advection near the surface. At this time it is possible for sea fog to appear. On the contrary, the cold advection increases the negative value of near-surface temperature difference to diminish the sea fog.

What is also shown in Fig.1 is presented as follows. (1) The sea fog does not always occur when the negative near-surface temperature difference decreases or turns positive every time, implying the corresponding relationship between the two variables is not exactly established. Thus the prediction of sea fog is so complex that multi-variable predictors should be taken into consideration. (2) The near-surface temperature difference is similar in variation tendency, but the sea fog is different, suggesting that the occurrence of sea fog has clear regional feature. Even so, the denotation of near-surface temperature difference is clear, which can

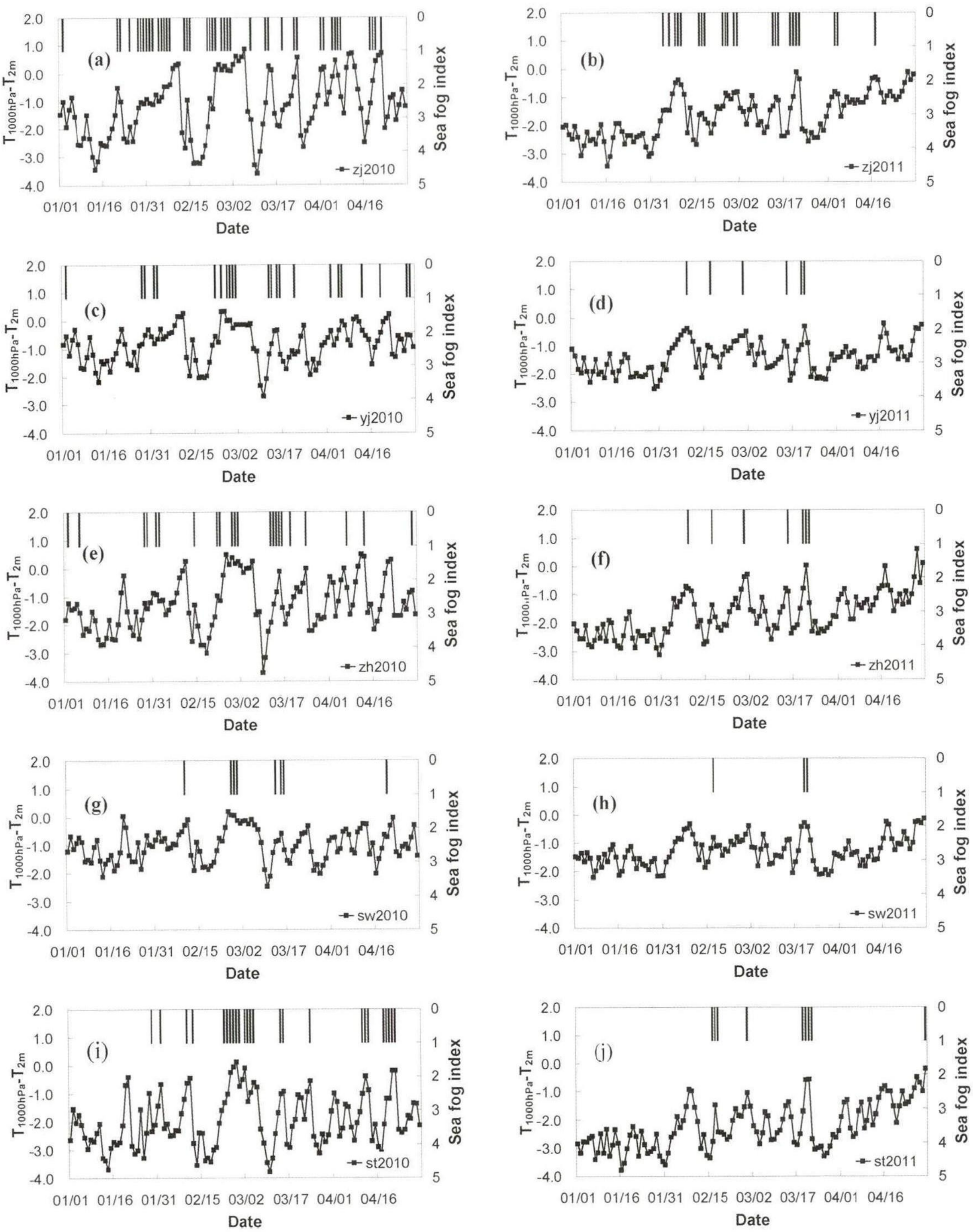

Figure 1. Relationship between the near-surface temperature difference and the occurrence of sea fog. The left ordinates are for the near-surface temperature difference ($T_{1\,000\ \mathrm{hPa}}-T_{2\ \mathrm{m}}$, units: K). The right ordinates are for the index of sea fog occurrence (0 for no sea fog and 1 for sea fog occurrence). The left column ((a), (c), (e), (g), (i)) is for the situation in 2010, while the right column ((b), (d), (f), (h), (j)) for 2011. (a) and (b): Zhanjiang; (c) and (d): Yangjiang; (e) and (f): Zhuhai; (g) and (h): Shanwei; (i) and (j): Shantou.

be used tentatively in the regional prediction of sea fog as a single predictor.

4 REALIZING THE PREDICTOR OF NEAR-SURFACE TEMPERATUR IN GRAPES MODEL

4.1 *Simulation of near-surface temperature difference in GRAPES model*

The analysis of NCEP reanalysis and station observation datasets mentioned above suggests that the near-surface temperature can be treated as a relatively independent predictor with decipherable physical connotation. The realization of this predictor in GRAPES model depends, however, on how well this model simulates the near-surface temperature.

Case study demonstrates that an evident event of sea fog takes place on the Guangdong coast from 19 to 22 March as observed at the 5 specific sites, which has large area and long duration. Fig.2 displays the prediction result of near-surface temperature difference. The result of 24-h prediction at 0000 UTC on 17 March and 0000 UTC on 19 March is shown in Fig.2 (a & b), respectively. Note that the observed sea fog does not occur at 0000 UTC on 17 March, but takes place on the whole Guangdong coast at 0000 UTC on 19 March. Comparison between Fig.2a and Fig.2b shows that the near-surface temperature difference is less than -1.0 K without sea fog (Fig.2a), but it is higher than -0.5 K when the sea fog controls the Guangdong coast (Fig.2b). As a result, the near-surface temperature difference is quite distinct between the situation with and without the sea fog.

The statistical analysis in Fig.3 also shows that the change tendency of 24-h prediction of near-surface temperature difference resembles that of NCEP reanalysis dataset over the 5 specific areas on the Guangdong coast from 2010 to 2011. Thus the GRAPES model is able to reflect the predictor of near-surface temperature difference.

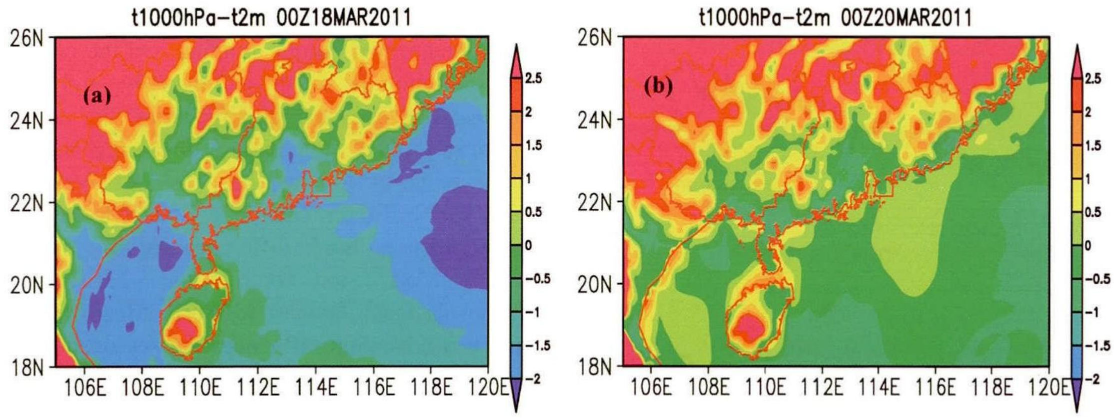

Figure 2. 24-h prediction of near-surface temperature difference ($T_{1\,000\,hPa}$–$T_{2\,m}$) in GRAPES model (units: K) (a): 24-h prediction at 0000 UTC on 17March (no marine fog); (b): 24-h prediction at 0000 UTC on 17March (sea fog occurs).

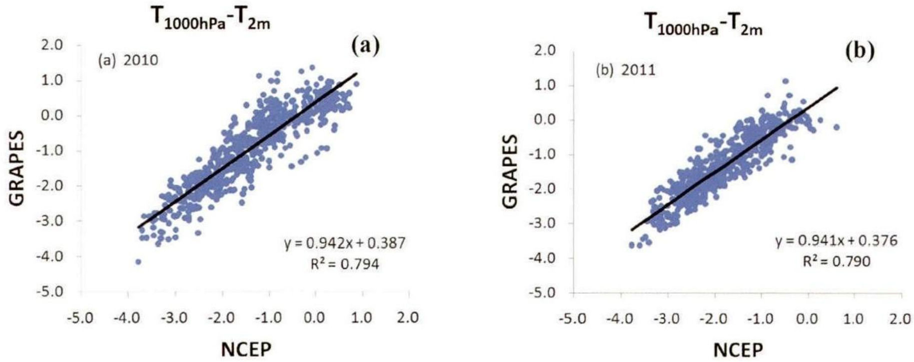

Figure 3. Simultaneous linear regression of 24-h prediction in GRAPES model to the NCEP reanalysis dataset over the 5 specific sites on the Guangdong coast (a: 2010; b: 2011).

4.2 *Introducing the predictor of near-surface temperature difference into the GRAPES model*

Before introducing the near-surface temperature difference into the model, it is necessary to understand its scale first. Here the 1°×1° NCEP reanalysis data from 2000 to 2011 is used to analyze the scale of near-surface temperature difference.

The climatological mean (2000 to 2011) seasonal variation of near-surface temperature difference ($T_{1\,000\,hPa}$–$T_{2\,m}$) over the specific sites on the Guangdong coast is shown in Fig.4. Results have the following revelation: (1) The near-surface temperature difference on the Guangdong coast changes from -3.0 K to 0.0 K over the specific areas because of the coarse resolution of NCEP reanalysis data. (2) Moreover, the negative value of near-surface temperature difference tends to decrease gradually with time. It is suggested that the 1 000-hPa air temperature increases faster than the near-surface air temperature under the influence of highly warm and wet air with the season shifts from winter to summer. (3) Besides, there are two jumps of near-surface temperature difference over the specific areas; the first one appears in the early February and the other one in mid-March. Then the time series of near-surface temperature over the specific areas can be divided into 3 phases.

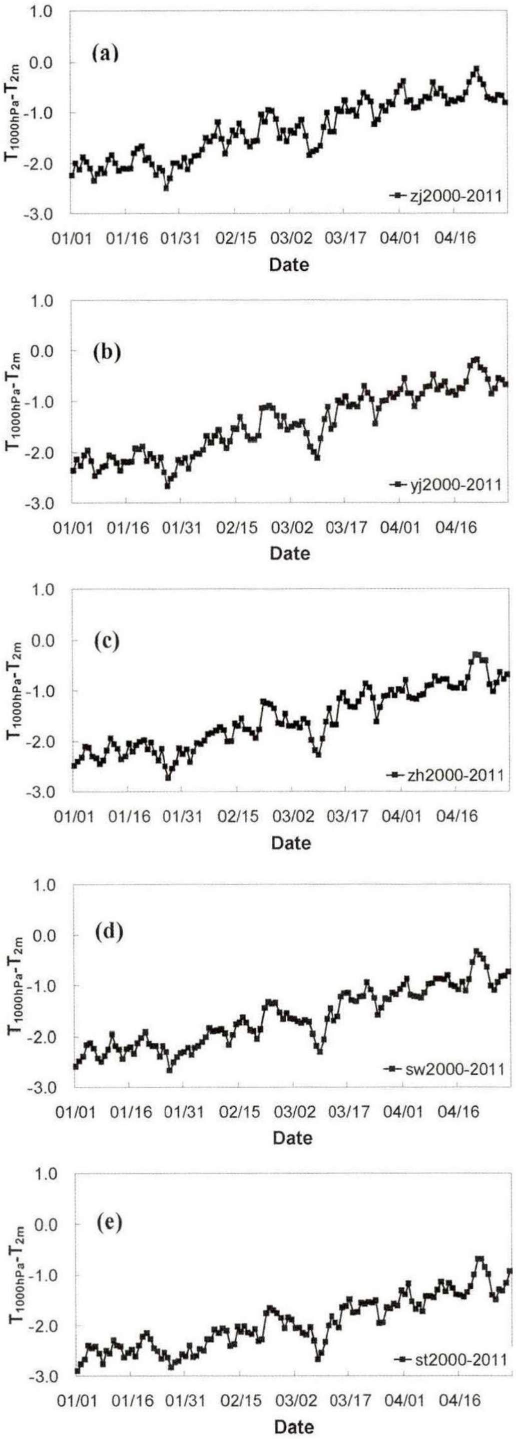

Figure 4. Time series of climate-mean (2000 to 2011) near-surface temperature difference ($T_{1\,000\,hPa}$-$T_{2\,m}$) from January to April over the specific areas. Units: K. (a): Zhanjiang; (b): Yangjiang; (c): Zhuhai; (d): Shanwei; (e): Shantou.

The near-surface temperature difference in the 3 phases over the specific areas is examined to understand its geographically distinct stage characteristics (Table 1). The 3 phases are defined as 1 January to 3 February, 4 February to 14 March, and 15 March to 30 April, respectively. The mean value of near-surface temperature difference from 1 January to 30 April is also calculated as reference. Table 1 shows that (1) the mean value is greatly different in the 3 stages, indicating that the warm and wet advection tends to be getting strong in the weather background; (2) the amplitude of the two jumps is quite different. The second jump is larger than the first one. The extent of the first jump is from 0.45 to 0.66 K, and that of the second jump is from 0.75 to 0.87 K. The difference between the two jumps indicates the transportation characteristic of warm and wet advection on the Guangdong coast. On the one hand, the transportation of warm and wet advection is featured by multi-stages and abrupt jumping. On the other hand, the transportation is enhanced gradually; and (3) for the mean value over the specific areas, the negative value of near-surface temperature difference increases from south to north. For instance, the mean value from January to April over Zhanjiang is 0.62 K larger than that over Shantou. Such difference reflects that the warm and wet advection controls the ocean near Leizhou Peninsula from January to April. Meanwhile the warm and wet advection influences the sea near Shantou from March to May. It is well consistent with the northward propagation of sea fog along the Chinese coast (Wang[16]).

The above analysis concentrates on the scale of near-surface temperature difference involved in the GRAPES model. The thresholds of near-surface temperature difference should be distinct over the specific regions in the 3 stages. The thresholds should be used to test the prediction of sea fog in practice after introducing the near-surface temperature difference into the GRAPES model. Then the systematic error of GRAPES model is included in the predictor of near-surface temperature difference finally.

The formula used in the GRAPES model is as follows:

$$\Delta T = T_{1\,000\,hPa} - T_{2\,m} \qquad (1)$$

in which ΔT, $T_{1\,000hPa}$, and $T_{2\,m}$ are for the near-surface temperature difference, air temperature at 1 000 hPa and 2-m height, respectively. When there is warm and wet advection, the negative value of ΔT is small or positive. The cold advection is corresponding to the large negative value of ΔT.

The near-surface temperature difference over the specific areas is calculated according to the following formula including the latitude and longitude of the ocean near the representative stations:

$$\Delta T_{i1,j1}=(\Delta T_{i-1,0}+\Delta T_{i+1,0}+\Delta T_{0,j-1}+\Delta T_{0,j+1}+\Delta T_{i,j})/5 \qquad (2)$$

in which $\Delta T_{i1,j1}$ is for the mean near-surface temperature difference over the specific district, $\Delta T_{i,j}$ is for the near-surface temperature difference on the center of oceans near the specific district, $\Delta T_{i-1,0}$, $\Delta T_{i+1,0}$, $\Delta T_{0,j-1}$ and $\Delta T_{0,j+1}$ are for the near-surface temperature differences on the grid around the center. The basic criteria deter-

Table 1. The climate-mean (2000 to 2011) near-surface temperature difference ($T_{1000\ hPa}$-$T_{2\ m}$) over the specific areas on the Guangdong coast (units: K).

Phases	Phase 1(1 Jan. to 3 Feb.)	Phase 2-Phase 1	Phase 2 (4 Feb. To 14 Mar.)	Phase 3-Phase 2	Phase 3 (15 Mar. To 30 Apr.)	All periods (1 Jan. to 30 Apr.)
Zhanjiang	−2.06	+0.65	−1.41	+0.75	−0.66	−1.34
Yangjiang	−2.21	+0.66	−1.55	+0.85	−0.70	−1.45
Zhuhai	−2.26	+0.55	−1.71	+0.87	−0.84	−1.57
Shanwei	−2.29	+0.53	−1.76	+0.82	−0.94	−1.63
Shantou	−2.54	+0.45	−2.09	+0.78	−1.31	−1.96

mined by the practical experience of model prediction is $\Delta T_{i1,j1} \geqslant -1.8$ K from January to March, and $\Delta T_{i1,j1} \geqslant -0.5$ K in April.

5 PREDICTION TESTS

After realizing the near-surface temperature difference in the GRAPES model, we compare the 24-h prediction of marine fog with and without the predictor of near-surface temperature difference in 2010 and 2011, when the sea fog occurs more and less frequently on the Guangdong coast, respectively (Tables 2 to 5). Tables 2 and 4 respectively show the forecast score of 24-h prediction in 2010 and 2011 using the regional numerical forecast products of sea fog on the Guangdong coast without the predictor of near-surface temperature difference. The higher forecast score in 2011 is due to the improvement of predictors in the model. Tables 3 and 5 presents the forecast score with the predictor of near-surface temperature difference in 2010 and 2011, respectively. Results show that the prediction accuracy,

Table 2. Forecast score of 24-h regional prediction products of sea fog on the Guangdong coast from January to April in 2010 (before improvement).

Region	Sample number	Correct prediction (fog)	Correct prediction (no fog)	Empty forecast	Missing forecast	Prediction accuracy	Risk score (Ts)	Hss
Zhanjiang	120	15	69	9	27	70%	0.29	0.27
Yangjiang	120	11	89	8	12	83%	0.35	0.42
Zhuhai	120	10	82	24	4	78%	0.37	0.40
Shanwei	120	3	84	28	5	73%	0.08	0.05
Shantou	120	14	75	21	10	75%	0.33	0.34
Average	120	11	80	18	12	76%	0.28	0.30

Table 3. The same as Table 2 but after the improvement.

Region	Sample number	Correct prediction (fog)	Correct prediction (no fog)	Empty forecast	Missing forecast	Prediction accuracy	Risk score (Ts)	Hss
Zhanjiang	120	29	69	9	13	82%	0.57	0.59
Yangjiang	120	13	85	12	10	82%	0.37	0.43
Zhuhai	120	5	111	2	2	97%	0.56	0.48
Shanwei	120	3	100	12	5	86%	0.15	0.19
Shantou	120	17	83	12	8	83%	0.46	0.52
Average	120	13	90	9	8	86%	0.42	0.44

Table 4. Forecast score of 24-h regional prediction products of sea fog on the Guangdong coast from January to April in 2011 (before improvement).

Region	Sample number	Correct prediction (fog)	Correct prediction (no fog)	Empty forecast	Missing forecast	Prediction accuracy	Risk score (Ts)	Hss
Zhanjiang	120	13	86	11	10	83%	0.38	0.44
Yangjiang	120	3	106	8	3	91%	0.21	0.31
Zhuhai	120	5	107	6	2	93%	0.38	0.52
Shanwei	120	2	113	4	1	96%	0.29	0.43
Shantou	120	3	110	1	6	94%	0.30	0.44
Average	120	5	104	6	4	91%	0.31	0.43

Table 5. Same as Table 4 but after the improvement.

Region	Sample number	Correct prediction (fog)	Correct prediction (no fog)	Empty forecast	Missing forecast	Prediction accuracy	Risk score (Ts)	Hss
Zhanjiang	120	13	90	7	10	86%	0.43	0.52
Yangjiang	120	4	104	10	2	90%	0.25	0.35
Zhuhai	120	4	112	1	3	97%	0.50	0.65
Shanwei	120	2	117	0	1	99%	0.67	0.80
Shantou	120	4	109	2	5	94%	0.36	0.50
Average	120	5	106	4	4	93%	0.44	0.56

Ts and Hss scores [29] are all improved for both the specific areas and the whole region after involving the predictor of near-surface temperature difference.

Meanwhile, the 24-to-48-h forecast score of related numerical prediction products is evidently improved (Table omitted), suggesting that the near-surface temperature difference is an efficient and pivotal predictor for the forecast of sea fog on the Guangdong coast.

6 CONCLUSIONS AND DISCUSSION

This paper starts with the analysis of relationship between the near-surface temperature difference ($T_{1000\,hPa}-T_{2\,m}$) and the occurrence of marine fog. Then we investigate the scale of near-surface temperature difference over the forecast regions on the Guangdong coast. Besides, the predictor of near-surface temperature difference output by GRAPES model is used to improve the regional prediction of sea fog on the Guangdong coast.

(1) The near-surface temperature difference well corresponds with the occurrence of marine fog. The near-surface temperature difference is high during the sea fog occurrence. The negative value of near-surface temperature difference evidently diminishes or even turns positive, suggesting the warming air is attributed to the gradual enhancement of warm and wet advection near the surface. Thus it is possible for the sea fog to take place. On the contrary, the increased negative value of near-surface temperature difference due to the cold advection makes the sea fog disappear.

(2) The scale analysis of near-surface temperature difference over the specific areas shows that the warm and wet advection, which intensifies gradually, is featured by multiple stages and jumping processes. In the meantime, the northward advancing of warm and wet advection is consistent with the propagation of sea fog along the Chinese coast from south to north.

(3) The near-surface temperature difference can be well simulated by the GRAPES model. The prediction accuracy, scores of Ts and Hss of regional prediction of sea fog on the Guangdong coast are all improved significantly in 2010 and 2011. It is demonstrated that the near-surface temperature difference is an efficient and key predictor for the sea fog forecast on the Guangdong coast.

Although the numerical forecast of the marine fog has achieved some progress by now, it is not good enough in practice (Zhou et al.[30]). Therefore, the study on the numerical forecast of marine fog is still important for the marine fog prediction in future. The research on numerical forecast of fog in recent years has pointed out that the fog prediction is closely associated with the background of basic synoptic background [23]. The improvement of vertical resolution in the boundary layer can lead to a better simulation (Tardif[31]). Furthermore, Bergot[32] proposed that because the parameterization of micro-physical structure in fog is not perfect, the prediction of horizontal visibility would not be accurate even with the correct prediction of fog occurrence. Consequently, the study on the numerical forecast of fog should keep concentrating on the improvement of fog prediction, the research on the boundary layer and the parameterization of micro-physical structure in the fog.

REFERENCES:

[1] ZHOU Fa-xiu. Lecture on sea fog chapter 4-forecast of sea fog [J]. Ocean Forecast, 1986 (in Chinese).

[2] LEIPPER D F. Fog on the United States west coast: a review [J]. Bull Amer Met Soc, 1994, 75(2): 229-240.

[3] LEWIS J M, KORACIN D, REDMOND K T. Sea fog research in the United Kingdom and United States: A historical essay including outlook [J]. Bull Amer Met Soc, 2004, 85(3): 395-408.

[4] WILLETT H C. Fog and haze, their causes, distribution, and forecasting [J]. Mon Wea Rev, 1928, 56(11): 435-468.

[5] DOUGLAS C. Cold fogs over the sea [J]. Meteorol Mag, 1930, 65: 133-135.

[6] PETTERSSEN S. On the causes and the forecasting of the California fog [J]. Bull Amer Met Soc, 1938, 19(1): 49-55.

[7] LEIPPER D F. Fog forecasting objectively in the California coastal area using LIBS [J]. Wea Forecast, 1995, 10(4): 741-762.

[8] PEAK J E, TAG P M. An expert system approach for prediction of maritime visibility obscuration [J]. Mon Wea Rev, 1989, 117(12): 2 641-2 653.

[9] TAG P M, PEAK J E. Machine learning of maritime fog forecast rules [J]. J Appl Meteorol, 1996, 35(5): 714-724.

[10] KOZIARA M C, RENARD R J, THOMPSON W J. Estimating sea fog probability using a model output statistics scheme [J]. Mon Wea Rev, 1983, 111(12): 2 333-2 340.

[11] HU Ji-fu, GUO Ke-cai, YAN Li-nong. Discriminate prediction of sea fog occurrence using a model output statistics scheme [J]. Periodical Ocean Univ China, 1996, 4:

439-445 (in Chinese).

[12] BERGOT T, CARRER D, NOILHAN J, et al. Improved site-specific numerical prediction of fog and low clouds: a feasibility study [J]. Wea Forecast, 2005, 20 (4): 627-646.

[13] Ré MY S, BERGOT T. Ensemble Kalman filter data assimilation in a 1D numerical model used for fog forecasting [J]. Mon Wea Rev, 2010, 138(5): 1 792-1 810.

[14] YANG D, RITCHIE H, DESJARDINS S, et al. High Resolution GEM-LAM application in sea fog prediction: Evaluation and diagnosis [J]. Wea Forecast, 2010, 25(2): 727-748.

[15] HEO K Y, HA K J. A coupled model study of formation and dissipation of sea fog [J]. Mon Wea Rev, 2010, 138 (4): 1 186-1 205.

[16] WANG Bin-hua. Sea Fog [M]. Beijing: Ocean Press, 1983, 59-102 (in Chinese).

[17] GULTEPE I, TARDIF R, MICHAELIDES S C, et al. Fog research: A review of past achievements and future perspectives [J]. J Pure Appl Geophys, 2007, 164: 1 121-1 159.

[18] TAYLOR G I. The formation of fog and mist [J]. Quart J Roy Meteor Soc, 1917, 43: 241-268.

[19] RODHE B . The effect of turbulence on fog formation [J]. Tellus, 1962, 14: 49-86.

[20] PILIé R J, MACK E J, ROGERS C W, et al. The formation of sea fog and the development of fog-stratus systems along the California coast [J]. J Appl Meteorol, 1979, 18(10): 1 275-1 286.

[21] ZHANG S P, XIE S P, LIU Q Y, et al. Seasonal variations of Yellow Sea fog: Observations and mechanisms [J]. J Climate, 2009, 22(24): 6 758-6 772.

[22] REN Zhao-peng, ZHANG Su-ping. Structure characteristics of the yellow sea summer fog in the boundary layer and the comparison with Spring fog [J]. Periodical Ocean Univ China, 2011, 41(5): 23-30 (in Chinese).

[23] GAO S H, LIN H, SHEN B, et al. A heavy sea fog event over the Yellow Sea in March 2005: Analysis and numerical modeling [J]. Adv Atmos Sci, 2007, 24: 65-81.

[24] HUANG Jian, WANG Bin, ZHOU Fa-xiu, et al. Turbulent heat exchange in a warm sea fog event on the coast of South China [J]. Chin J Atmos Sci, 2010, 34 (4): 715-725 (in Chinese).

[25] HUANG H J, LIU H N, JIANG W M, et al. Characteristics of the boundary layer structure of sea fog on the coast of southern China [J]. Adv Atmos Sci, 2011, 28(6): 1 377-1 389.

[26] HUANG Hui-jun, HUANG Jian, LIU Chun-xia, et al. Prediction of seafog of Guangdong coastland using the variable factors output by GPAPES model [J]. J Trop Meteorol, 2010, 26(1): 31-39 (in Chinese).

[27] DING Wei-yu, WAN Qi-lin, YAN Jing-hua, et al. Impact of the initialization on mesoscale model prediction in South China [J]. J Trop Meteorol, 2006, 22(1): 10-17 (in Chinese).

[28] CHEN Zi-tong, WAN Qi-lin, SHEN Xue-shun, et al. Comparisons and improvement of water vapor advection schemes of GRAPES regional model [J]. J Trop Meteorol, 2010, 26(1): 1-6 (in Chinese).

[29] Writing group of Guangdong Meteorological Service. Manual of Weather Forecast Technology in Guangdong Province [M]. Beijing: China Meteorological Press, 2006: 416-419 (in Chinese).

[30] ZHOU B B, DU J, GULTEPE I, et al. Forecast of low visibility and fog from NCEP: Current status and efforts [J]. J Pure Appl Geophys, 2012, 169: 895-909.

[31] TARDIF R. The impact of vertical resolution in the explicit numerical forecasting of radiation fog: A case study [J]. J Pure Appl Geophys, 2007, 164: 1 221-1 240.

[32] BERGOT T. Quality assessment of the Cobel-Isba numerical forecast system of fog and low clouds [J]. J Pure Appl Geophys, 2007, 164: 1 265-1 282.

Citation: HUANG Hui-jun, HUANG Jian, LIU Chun-xia, et al. Improvement of regional prediction of sea fog on Guangdong coastland using the factor of temperature difference in the near-surface layer [J]. J Trop Meteorol, 2016, 22(1): 66-73.