A Preliminary Report on Numerical Simulation of Synoptic Scale Atmospheric Motion and the Associated Sensible and Latent Heat Supplies from Sea Surface during the AMTEX '74 Period*

by

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(Received July 2, 1974, and Revised October 17, 1974)

Abstract

Using an operational numerical weather prediction model at the Japan Meteorological Agency, i.e., a 6-level, fine-mesh, limited area primitive equation model***, a preliminary study was made with regard to the numerical simulation of synoptic scale atmospheric motion during the AMTEX '74 period. As the first phase of the investigation, three cases are taken up for the case study. The first case (Case 1) shows the passage of a moving anticyclone and a cyclone over the East China Sea. The second case (Case 2) is the case of a front passage in the Okinawa area. The third case (Case 3) is featured by the predominant coverage of the whole AMTEX area by a cold air mass. Calculated patterns of the three cases show, in general, good agreement with observed patterns.

The second phase of the investigation elaborates comparison of the synoptic scale sensible and latent heat supplies from the sea surface in the model atmosphere in the cases mentioned above. The bulk aerodynamic method is employed for the estimation of the sensible and latent heat supplies which are quite sensitive to the synoptic situation. The model atmosphere also well simulates the day-to-day variation of the supplies. The hour-to-hour variation in the model atmosphere, however, is not moderate as in the case of the real atmosphere, but shows a sharp decrease in the intensity as time advances. This may be a deficiency of the model in responding to external heating. The calculated total quantity of heat supplies during 24 hours compares favorably with the preliminary calculation of heat supplies from the AMTEX '74 observation by J. Kondo (1974).

A comparison is made between the 24-hour forecast with the normal sea surface temperature and that with the 8-day mean sea surface temperature of 87–28 February 1974. No appreciable difference is seen in prognostic patterns of meteorological variables such as pressure, wind velocity, temperature, humidity and quantity of precipitation as far as the 24-hour forecast is concerned. However, the distribution of sensible and latent heat supplies shows a significant discrepancy between the two cases.

* This study was made as a part of the AMTEX Research Program of Japan.
** Concurrently appointed to the Meteorological Research Institute.
*** Hereafter, the model will be designated as 6L-FLM.
1. Introduction

Since October 1, 1973, a six-level, fine-mesh, limited area primitive equation model has been in operational use at the Japan Meteorological Agency as one of the two models for routine numerical weather prediction. Description of the 6L-FLM is given in the AMTEX Report No. 3 (1973), and also in more detail in the Appendix attached to the Periodic Report on Numerical Weather Prediction, XIII (1973) issued by the Japan Meteorological Agency. Formulation of the physical processes employed in the model is given in the appendix to the present paper.

During the past eight months through fall, winter, spring and pre-summer, we have observed the daily performance of the model. Out of these experiences have emerged several defects of the model. For instance, the remarkable air-mass transformation process in the Sea of Japan during the winter season was not well simulated. After the outburst of a cold air mass from the continent, the southeastern part of the Sea of Japan and the Japan Sea side of the Japanese Islands were covered by dense clouds, and heavy snowfalls were often observed. The prognostic chart obtained by the model, however, does not show definitely the distribution of cloudiness and the snowfalls. Surface pressure patterns for the medium scale disturbance are also insufficiently simulated by the model. The lateral boundary condition is another ex-

Fig. 1. The AMTEX area and the forecast domain of 6L-FLM (the interior rectangle covered by the grid net of grid size =152.4km.). The outer rectangle, resolved by a grid interval double that of 6L-FLM, denotes the forecast domain for a 6-level quasi-geostrophic model which provides the lateral boundary value to 6L-FLM.
ample of the problem to be solved. Under these circumstances, we are now concentrating on improvement of the physical processes in the model and refinement of the computational technique.

As a preliminary survey on the simulation of synoptic scale motion over the AMTEX area, we will present in this paper the results of the prognosis by the 6L-FLM and examine the simulated procedure of large scale air-mass modification in the model atmosphere. Special emphasis is put on the verification of the calculated sensible and latent heat supplies from the East China Sea against the observation obtained during the AMTEX '74 period.

The bulk aerodynamic method is used in the present model for the estimation of the supplies. Relatively speaking, the bulk method is considered to be a useful parameterization of the turbulent transfer process in the surface boundary layer. In the present study, we aim at examining the time sequence of the heat supplies in the model atmosphere and comparing the calculated daily total of the heat supplies with the preliminary observation obtained by Kondo (1974).

The initial value for numerical weather prediction did not take account of the special observation of AMTEX except two radiosonde soundings transmitted via operational telecommunication line. Fig. 1 shows the location of the AMTEX area in the forecast domain of 6L-FLM.

In the present paper, the performance of the model in simulating synoptic scale atmospheric motion is first examined. We took up three cases for case study and the results are presented in section 2. Section 3 illustrates the distribution of air-ocean exchange of sensible and latent heats. Problems associated with accurate incorporation of the air-mass transformation process in the numerical model are discussed in section 4.

2. Case studies

The following three cases are taken up as examples of case study;
Case 1: 00 GMT 18-00 GMT 19 Feb. 1974,
Case 2: 00 GMT 23-00 GMT 24 Feb. 1974,
Case 3: 00 GMT 26-00 GMT 27 Feb. 1974.

In the first case (Case 1), a moving anticyclone passed over the East China Sea towards the east and a cyclone developed afterward. Weather over the AMTEX area was generally fine on these two days. This case is chosen as one of the cases in which the air-ocean interaction was relatively inactive.

As is shown in Fig. 2, the model reproduced rather well the actual change of atmospheric motion except the speed of cyclone movement. As to the forecast amount of precipitation, comparison is made between the two cases (Fig. 3). The one was calculated under a constraint on the maximum values of sensible and latent heat supplies, and the other free from them. The constraint is actually posed on the difference between the sea surface temperature, \( T_{\text{sea}} \), and the air temperature at the lowest level, \( T_{\text{air}} \), as \( |T_{\text{sea}} - T_{\text{air}}| < 10^\circ \text{C} \).

We may say that the calculated quantity of precipitation is considerably influenced by assumptions on the physical processes in the model atmosphere. Especially, the area of rainfall may be easily expanded or shrunk depending on the assumption.
Fig. 2. The surface pressure $P_s$ (mb) and the geopotential at 500 mb $Z_{500}$ (m) in Case 1, 00 GMT 18-00 GMT 19 Feb. 1974. (a) Initial patterns of $P_s$ (solid line) and $Z_{500}$ (dashed line), valid at 00 GMT 18 Feb. 1974. (b) The 24-hour forecast of $P_s$ (solid line) and $Z_{500}$ (dashed line), valid at 00 GMT 19 Feb. 1974. (c) Verification chart of $P_s$ (solid line) and $Z_{500}$ (dashed line) for Case 1, valid at 00 GMT 19 Feb. 1974.
As is well known, the observed amount of rainfall is usually ten or more times larger than that calculated. In view of the differences in the physics of rainmaking between the real and the model atmosphere, we may say that the quantity of precipitation is naturally smaller in the calculation.

The second case (Case 2) is concerned with the passage of a pronounced frontal system through the Okinawa area 23rd. The cold air outbreak began afterward. We took up this case in order to examine the simulation of the front passage and to estimate the heat transfer from the sea surface at the initial stage of the remarkable air-mass transformation.

As is seen in Fig. 4, the model predicted the movement of the cold front with...
Fig. 4. The surface pressure $P_s$ (mb) and the geopotential at 500 mb $Z_{500}$ (m) in Case 2, 00 GMT 23—00 GMT 24 Feb. 1974. (a) The same as Fig. 2(a), but for 00 GMT 23 Feb. 1974, (b) The same as Fig. 2(b), but for 00 GMT 24 Feb. 1974, (c) The same as Fig. 2(c), but for 00 GMT 24 Feb. 1974.
sufficient accuracy. The small cyclone to the south of Japan is also well simulated in the prognosis. As to the forecast of precipitation, the similar comments as in Case 1 may made (Fig. 5).

Next, we will proceed to Case 3. Here, the anticyclone from the continent pushed out the cold air mass over the East China Sea and the western Pacific. A notable thermal modification of the air was taking place. Therefore, we adopted this case as a typical one for the air-mass transformation. The diagnostic study in the following sections is concentrated on Case 3. As is seen in Fig. 6, the synoptic situation is well reproduced in the prognostic charts. The approach of the cold air mass to the AMTEX area is also predicted (Fig. 7).

It should be noted that a conspicuous downward current predominated in the upper and middle troposphere over the East China Sea and the Sea of Japan, where active upward transport by convection of sensible and latent heat was taking place. As
Fig. 6. The surface pressure $P_s$ (mb) and the geopotential at 500 mb $Z_{500}$ (m) in Case 3, 00 GMT 26-00 GMT 27 Feb. 1974, (a) The same as Fig. 2(a), but for 00 GMT 26 Feb. 1974, (b) The same as Fig. 2(b), but for 00 GMT 27 Feb. 1974, (c) The same as Fig. 2(c), but for 00 GMT 27 Feb. 1974.
will be mentioned later, this downward motion had a remarkable effect on the convection activity in the lowest layer of the model atmosphere. In other words, the existence of strong downward velocity evidently distinguishes the effect of the convection group in the middle latitudes from that in the low latitudes.

Over the East China Sea and the Sea of Japan, the planetary boundary layer is moist due to active vertical transport of water vapor as well as sensible heat under the outburst of a cold and dry air mass from the continent over the warm sea. Thus, we often observe bad weather there. This trend is indicated in the prognostic chart of precipitation in the case of no constraint (Fig. 8(b)).

In order to demonstrate the effect of the non-adiabatic heating from the sea surface, we calculated again Case 3, excluding sensible and latent heat supplies. We found remarkable differences in the surface pressure field (Fig. 9) and the temperature field (Fig. 10) between the cases with and without heat supplies. Especially, over the southern part of the East China Sea, we see that the case excluding heat supplies showed higher surface pressures with a maximum difference of more than 4 mb and lower temperatures at the 850 mb level with a maximum deviation of more than 3°C, than the case including heat supplies. Needless to say, prognostic charts in the case with heat supply are superior to those without.

3. Distribution and variation of sensible and latent heat supplies

The amount of sensible and latent heat supplies from the sea surface into the model atmosphere during 24 hours is summed up for Cases 1, 2 and 3, respectively (Figs. 11 and 12). First of all, we notice that the distribution of latent heat supply as well as sensible heat supply is quite changeable on the daily basis, depending on an overlying synoptic situation.

In Case 1, relatively warm air covers the East China Sea. On the other hand, in Case 2, predominant cold air comes down toward the south to cover the Yellow Sea,
the East China Sea and the Sea of Japan. Therefore, the sensible and latent heat supplies show sharp increase in intensity over an area where the difference between the surface-air and sea-surface temperatures is largest.

As we had expected, Case 1 received minor heat supplies from the sea surface, while Cases 2 and 3 obtained quite a large amount of heat. Furthermore, we may notice that the distribution of heat supplies at the initial stage of the outbreak (Case 2) differs remarkably from that at the mature stage (Case 3). At the former stage, the maximum of the computed sensible heat supply becomes more than 600 ly/day. The zone of strong heat supply lies over the northern part of the East China Sea and the western part of the Sea of Japan. This indicates the active warming of the fresh cold air mass just after leaving the continent. On the other hand, as the cold air mass comes to cover the ocean completely (i.e. at the latter stage), the maximum value of sensible heat supply decrease and the zone of active supply shifts
southward to cover the southern part of the East China Sea. This indicates a feature of the air-mass transformation process over the warm sea. As the cold air mass spreads out further over the sea, the gradually modified air mass results in a maximum temperature difference between the air and the ocean at the sea surface over near the Kuroshio current rather than over the northern part of the East China Sea where the maximum temperature difference was observed at an earlier stage.

It is really interesting to compare the heat supplies experienced by the model atmosphere (Figs. 11 and 12) with those based on the heat budget method (Kondo,
Fig. 11. The 24-hour accumulated amount of sensible heat supply for (a) Case 1, (b) Case 2, and (c) Case 3, (Unit: ly/day).

Fig. 12. The 24-hour accumulated amount of latent heat supply for (a) Case 1, (b) Case 2, (c) Case 3, (Unit: 0.1 mm/day). If multiplied by 6, the label becomes the numeric in unit of ly/day and if divided by 10, in unit of mm/day.
Kondo performed a rough estimation of the heat supplies from the sea surface of the AMTEX area from 14 through 28 February 1974. On 18th, 23rd and 26th Feb., he obtained on an average a sensible heat transfer from the sea surface into the atmosphere of 37, 147 and 395 ly/day, respectively. As to the latent heat supply, his estimate indicates a vertical transport of 204, 376 and 813 ly/day or 38, 63 and 136 (0.1 mm)/day, respectively. Although Kondo's estimate is not a final result, we may say that the agreement of the two heat supplies over the AMTEX area is satisfactory.

Next, in order to investigate the thermodynamic reaction of the model atmosphere to the external heat source, we examined the 1-hour accumulated amount of calculated sensible heat supply for 24 hours in Case 3. We notice that the quantity of the supply decreases sharply with the advance of time. When we compare the 1-hour accumulated amount of calculated sensible heat supply from HR23 to HR24 on 26th with that from HR00 to HR01 on 27th, we see that the former is less than half of the latter, though these two should be close to each other because of proximity of time.

This discrepancy may be attributable firstly to the fact that at first the extrapolated surface air temperature from the above two levels (i.e., 800 and 900 mb) was rapidly warmed up as time advanced, mainly due to the rise of the temperature at the 900 mb level, and secondly to the fact that the supplied heat was not transported sufficiently above the 800 mb level into the middle troposphere. The first defect may be eliminated by changing the method of estimating the surface air temperature, but the second is more serious, being closely associated with the parametrization of convective activity in group in the model atmosphere.

4. Air-mass transformation process and numerical modeling

The present study is mainly concerned with the preliminary verification of the sensible and latent heat supplies estimated by the bulk aerodynamic method in the 6L-FLM.

From the results of calculation of the sensible and latent heat supplies in the model atmosphere shown in the previous section, we may say that the model atmosphere promptly responds to the heating from the sea surface and is quick to get into a state of quasi-thermal equilibrium. This may not be the case in the real atmosphere. We may presume that the synoptic scale motion in the real atmosphere reacts to the external heat source quite slowly and the quantity of heat supply per unit time must be always nearly constant on the hour-to-hour basis. The distribution and the magnitude of heat supply in the real atmosphere are thus considered to vary gradually with the time scale of a day.

As far as the daily grand total is concerned, however, the quantity of heat supplies calculated by the bulk method seems to be reasonable. Furthermore, Bowen's ratio calculated from the heat supplies mentioned above shows acceptable values, that is: 1–2 over the Sea of Japan, 0.5–1 over the East China Sea, and 0.6 or less over the western Pacific.

Therefore, the bulk aerodynamic method adopted in the present model appears to
be a useful parameterization of the surface boundary layer. It should be remarked that the coefficient used in the bulk method is not unique, but largely depends on the estimated surface wind speed. Consequently the total amount of daily heat supplies in the model atmosphere may vary as we modify the calculated wind speed at the surface.

In order to make the response to the heating be moderate, we have first to stabilize the magnitude of heat supplies per unit time in the model atmosphere. As was mentioned earlier, we have to improve the method of estimating the surface air temperature, \( T_{\text{air}} \). For the present, we obtain \( T_{\text{air}} \) from \( T_{800} \) and \( T_{900} \) by a linear extrapolation formula. In this particular atmosphere, the air at the 900 mb level tends to be quickly warmed up due to the vertical transport of sensible heat, while the temperatures at the 800 mb and above it do not change appreciably. Thus, the estimated surface air temperature is readily influenced by the increase of \( T_{900} \) and rapidly leads to high temperatures. This results in a sharp decrease in sensible and latent heat supplies from the sea surface according to the bulk method formula employed in the present model.

As to the modification of the air at the 800 mb and above it, we have to improve the parameterization scheme of the ensemble effect of convection so that more sensible heat and water vapor be transported up into the middle troposphere. According to the observational studies (e.g., NINOMIYA, 1968), in the air-mass transformation process under the outburst of cold air over the Sea of Japan, even the air at the 600 mb level is warmed and moistened. Furthermore, upward motion is observed over the Sea of Japan, while 6L-FLM mostly yields downward motion. Therefore, in the model atmosphere of 6L-FLM, the air at and above the 800 mb tends to be more and more dry as time advances.

The distribution of spots where moist convection took place during the 24 hours indicates its maximum occurrence over the southeastern part of the Sea of Japan along the Japanese main island and the eastern part of the East China Sea.

Presumably, the convection in this case is actually more penetrative than that simulated in the model atmosphere of 6L-FLM. We are now aiming at the refinement of the convection parameterization in the following directions:
1. to let the convective transport be more penetrative,
2. to incorporate the effect of mechanical turbulence.

In summary, as far as the large scale numerical modeling is concerned, we feel that the present bulk method is good enough for parameterizing the effect of the surface boundary layer. On the other hand, the method for taking account of the transporting or maxing mechanism in the upper planetary boundary layer and above it is not satisfactory. Furthermore, we should point out the importance of the difference in the mechanism of convective transport between the middle latitudes and the lower latitudes.

For the consideration of the numerical modeling of the air-mass transformation process, further studies regarding the behavior of the model atmosphere are needed. For example, we have to make a comparison of the temperature change in the lower atmosphere between calculation and observation. The magnitude of terms in the thermal equation is also a measure of simulation indicating the extent to which the numerical modeling achieves. Investigation involving these aspects will be reported later.
Finally, let us look at the deviation of the sea surface temperature in February 1974 from the normal (Fig. 13). Generally speaking, as is shown in Fig. 13(c), the sea surface temperature in this February was colder than the normal in the northwestern part of the East China Sea and the southern part of the Sea of Japan, while it was
warmer along the Kuroshio current. The deviation, however, hardly changes the predicted pressure and temperature patterns. Thus, when one is interested only in the short-range prognostic charts of synoptic scale patterns, one need not be worried about the fluctuation of the sea surface temperature. For Case 3, in which the air-mass transformation is more active than in any other case, we confirmed this fact. On the other hand, if the distribution and the magnitude of the heat supply are in question, the deviation is crucial in determining the configuration of the distribution (compare Fig. 14 with Fig. 11(c)). Furthermore, for the study and simulation of the behavior of medium scale and meso-scale disturbances and the related local weather phenomena, the specification of the real sea surface temperature may conceivably be significant. Extended forecast may be another example which needs the updated sea surface temperature.

Acknowledgements—The present authors are indebted to Mr. J. YAMAMOTO for his assistance in performing the numerical simulation. Thanks are also due to Mrs. H. SHINODA for drafting many figures.

APPENDIX

Physical Processes Formulated in the 6L-FLM

The detailed description of the 6L-FLM will be given elsewhere. For the sake of our readers' convenience, the formulation of physical processes employed in the model will be given below.

a) Friction

The exchange of momentum between air and earth's surface in the surface layer is expressed by the stress vector

$$\tau_m = \rho C'_{fr} |V_m| V_m$$

where $C'_{fr} = 0.7 C''_{fr}$ (which is specified later in c)(i)) and $V_m$ is the wind vector at $Z=Z_m$. Practically, $V_m$ is estimated by an extrapolation formula from wind at adjacent upper levels under the assumption that $V_m$ blows towards lower pressure area with a certain angle to $V_0$(i.e., $V_{999}$). The absolute value of $V_m$, $|V_m|$, on the right hand side is assumed not to be less than 2 m/s.
Additionally, we use the following stress at and above the 900 mb level, i.e.,

\[ \tau_m = \rho K_m \left( \frac{\partial V}{\partial z} \right)_{900} \]

\[ \tau = 0 \quad \text{for} \quad \rho \leq 800 \text{mb} \]

where \( K_m = \rho |\partial V/\partial z|_{900} \) and \( l = 30 \text{ m} \). Thus we may evaluate the frictional force \( F \) by

\[ \frac{1}{\rho} C_m l V \frac{\partial \tau}{\partial z}. \]

b) Sub-grid scale diffusion

Horizontal diffusion processes for momentum, sensible heat and specific humidity are introduced into the model. These eddy diffusion coefficients are all assumed to be same value based on the two-dimensional turbulence theory, i.e.,

\[ \nu = \gamma \mathbf{P} \xi d^3 \]

where \( \nu \) is the coefficient, \( \mathbf{P} \) the horizontal del-operator, \( \xi \) the vorticity, \( d \) the grid distance and \( \gamma \) is assumed to be unity.

c) Non-adiabatic heating and cooling

(i) Surface exchange of sensible heat between the lowest layer of the model atmosphere and the sea surface is evaluated by the bulk aerodynamic method. The coefficient of sensible heat flux is treated as a function of the static stability and wind speed as follows:

Sensible heat flux between the sea surface and the atmosphere, \( H_s \), may be given as

\[ H_s = \rho C_{p} V_m C_{p} |V_m| (T_{sea} - T_{air}) \]

where \( V_m \) is the wind at an altitude of \( Z_m \) and its absolute value is also assumed not to be less than 2 m/s. \( C''_{p} \) is specified and limited as

\[ C''_{p} = (1.0 + 0.0667 T) \times (0.833 + 0.084 |V_m|) \times 10^{-3} \leq 2 \times 10^{-3} \]

for the unstable and neutral case \((\Delta T = T_{sea} - T_{air} > 0)\)

and

\[ C''_{p} = (0.11 + 0.1111 T) \times (0.889 + 0.055 |V_m|) \times 10^{-3} \geq 10^{-4} \]

for the stable case \((\Delta T = T_{sea} - T_{air} < 0)\)

where \( T_{sea} \) denotes the sea surface temperature and \( T_{air} \), the temperature of air at an altitude of \( Z_a \).

(ii) Transport of latent heat (evaporation) is computed from transport of sensible heat by Bowen’s ratio relationship. We assumed that Bowen’s ratio depends on the temperature and relative humidity of the lowest layer.

(iii) Convective adjustment scheme similar to that proposed by GADD and KEERS (1970) is used for estimating the quantity of precipitation, heating due to release of latent heat and convective transport of heat and water vapor. At the grid point where the relative humidity is less than 50%, the dry adjustment is applied.

(iv) No radiative cooling is considered.

d) Orographic effect

Effect of orography at the ground surface is incorporated in the model assuming that the maximum height of the mountain is equal to 500 m. The constraint on the maximum height is put by the following reason. In the forecast domain of the 6L-FLM, there are highlands with a height of 1,000 m or more over the northwestern part. However, the 6-level quasi-geostrophic model which provides the lateral boundary condition to the 6L-FLM has no orographic effect. Therefore, we have to limit the maximum height of the plateau as mentioned above for the purpose of avoiding the noise from the boundary due to inconsistency in the treatment of orographic effect between the two models.
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AMTEX '74 期間中のシノプティック・スケールの大気運動の数値シミュレーションおよびそれに関連した海面からの
頭・潜熱補給量について（序報）
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気象庁の数値予報の現状モデル——アジア地区 6 層ファイン・メッシュ・ブリティック方程式モデルを用いて, AMTEX '74 期間中のシノプティック・スケールの大気運動の予備的数値シミュレーションを行なった。

本研究は大別して 2 段階にわけられる。第 1 段階はケース・スタディで, 期間中から 3 例を選びシミュレーションの結果を詳しく調べた。第 1 例は東シナ海の北部を通過する場合, 第 2 例は沖縄地方を通過する場合, 第 3 例は全 AMTEX 領域上を直接気流が通過している場合である。3 例の数値予報結果は, 謄して実験よく一致している。

研究の第 2 段階では, 3 例についてモデル大気中への海面からのシノプティックなスケールでみた頭・潜熱補給量をくらべてみた。補給量の計算にはパルサ法を用いている。補給量は, シノプティックな気候状況に大変敏感である。シミュレートした補給量は, 現実大気の日々変化をよく表わしているが, 時間変化の方はよくない。実況で徐々に変動しているのに対して, モデル大気では急激に減少する。これはモデル大気の外的熱源に対する反応がよくないからである。42 時間実積した補給量は, 近藤純正 (1974) が AMTEX '74 のデータから予備的に求めた値とよい対応を示している。

海水温のノルマからの偏倚が, どの程度予報値に影響を与えるかを調べるために, 1974 年 2 月 21 日から 28 日までの 8 日平均の海水表面温度を用いてシミュレーションした所, 予想天気図ではノルマの海水表面温度を用いた場合と差はなかった。シノプティック・スケールの大気運動の 24 時間予報に関する限り, 海水温のノルマからの偏倚は無視できよう。他方, 潮・潜熱の補給量の分布図には著しい違いがみられるので, 中小規模現象の予報や延長予報では, これらの偏倚は重要と考えられる。