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Prediction of SST for Operational Ocean Prediction System

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Abstract : A practical algorithm for prediction of the sea surface temperatures (SST) from the satellite remote sensing data is presented in this paper. The fluctuations of SST consist of deterministic normals and stochastic anomalies. Due to large thermal inertia of sea water, the SST anomalies can be modelled by autoregressive or Markov process, and its near future values can be predicted provided the recent values of SST are available. The actual SST is predicted by superposing the pre-known SST normals and the predicted SST anomalies. We applied this prediction algorithm to the NOAA AVHRR weekly SST data for 18 years (1981-1998) in the seas adjacent to Korea (115-145° E, 20-55° N). The algorithm is applicable not only for prediction of SST in near future but also for nowcast of SST in the cloud covered regions.

Key words : SST prediction, satellite remote sensing, Markov process model.

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1. Introduction

Ocean prediction system, based on three-dimensional numerical model and data assimilation, requires boundary conditions at the sea surface. Real time sea surface temperature (SST) and sea surface wind stress are required for a realistic ocean prediction model. Quasi-real time SST data are available by satellite remote sensing, provided the sea area of interest is not covered by clouds. A reliable prediction method of SST is essential for nowcast of SST in cloud areas and forecast of SST in the near future.

Variation of the SST is a combination of deterministic seasonal changes, which are represented by normals of SST, and stochastic anomalies, which are deviations of the SST from normals. The seasonal variation of SST is predictable for any time of the year at sites where the SST data are available for many years. The SST anomalies, on the other hand, are not deterministic. However, due to large thermal inertia of the sea water, the SST anomalies in the near future can be statistically predicted.

2. Difficuties in the prediction of SST

The local change of SST is affected by advection of heat, heat fluxes across the sea surface and the bottom of surface mixed layer (SML), and the horizontal and vertical diffusions of heat. The state equation of SST can be written as

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{Q_s + Q_m}{\rho c_p H} + K_h\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + K_v\frac{\partial^2 T}{\partial z^2}$$

where T is the SST, (u, v) are current velocities in the (x, y) direction, Q_s and Q_m are heat fluxes across the sea surface and the bottom of the SML, respectively, ρ is the water density, c_p is the specific heat, H is the thickness of the SML, and K_h and K_v are horizontal and vertical diffusivities of heat, respectively.

Prediction of SST by the above equation requires quantitative data on the amount of heat advection by ocean currents, and the heat fluxes across the sea surface and the bottom of the SML. Reliable informations on those required data are not available in real time. However, the SST data are available through satellite remote sensing. Our approach is to predict SST itself

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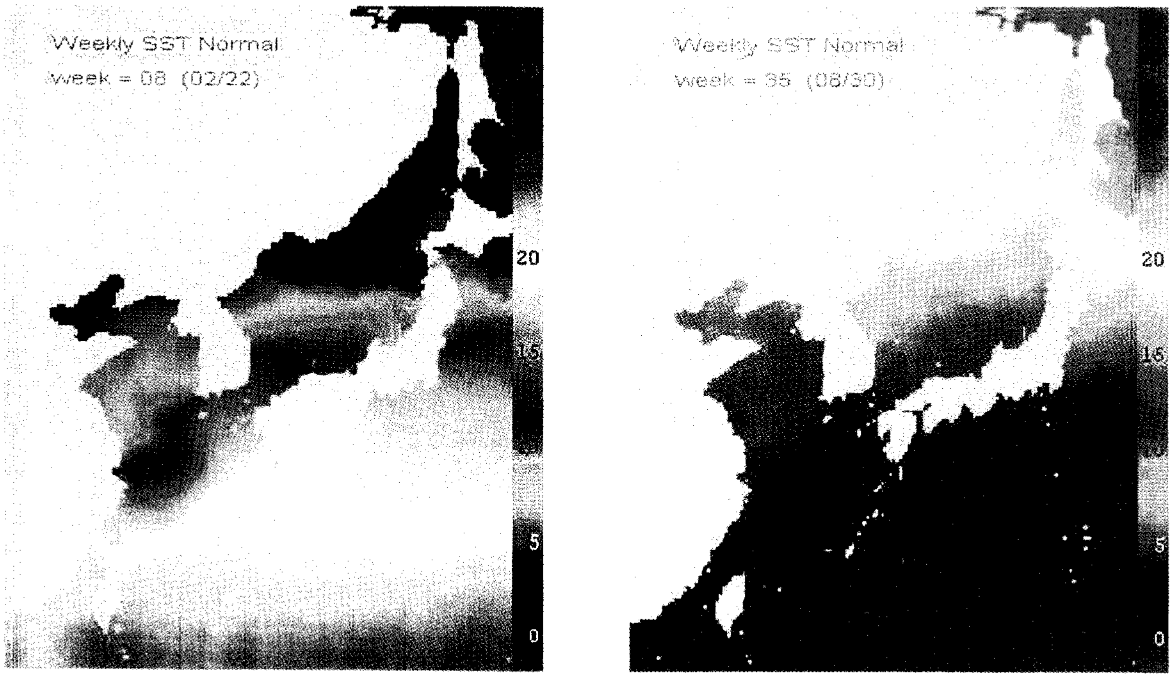

Fig. 1. SST normals in February (left) and August (right).

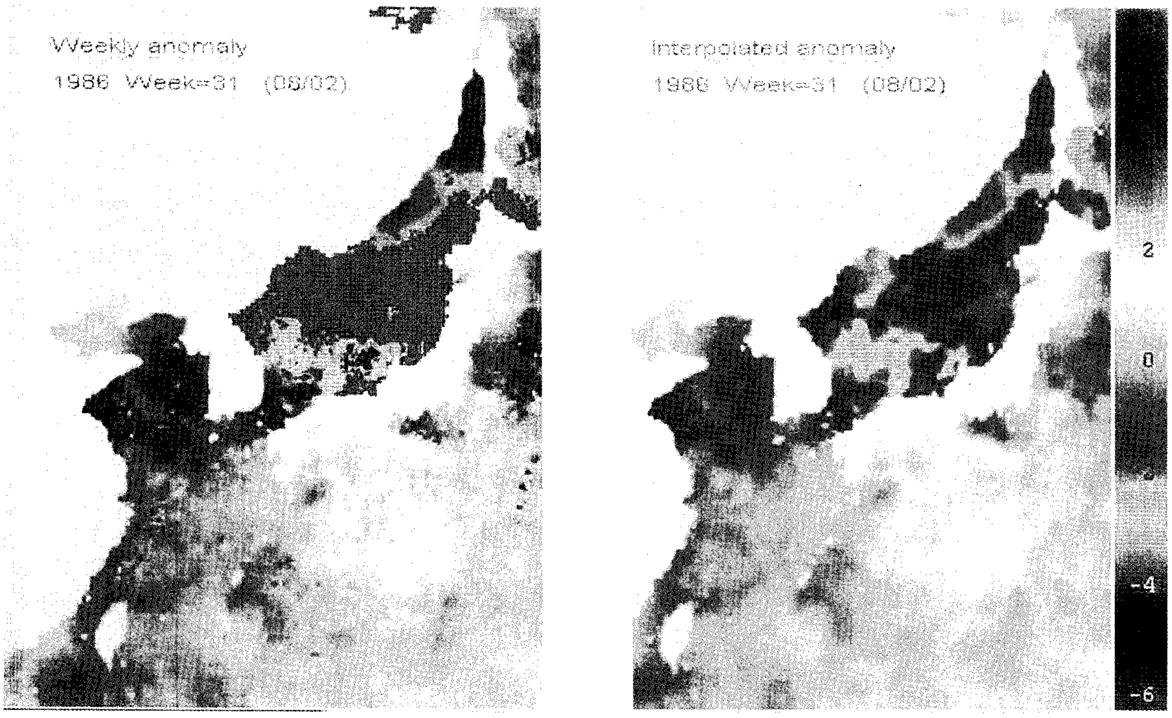

Fig. 2. Observed (left) and interpolated SST anomalies (right) at 31st week (August) of 1986. Erroneous data or cloud covered areas are shown by grey color.

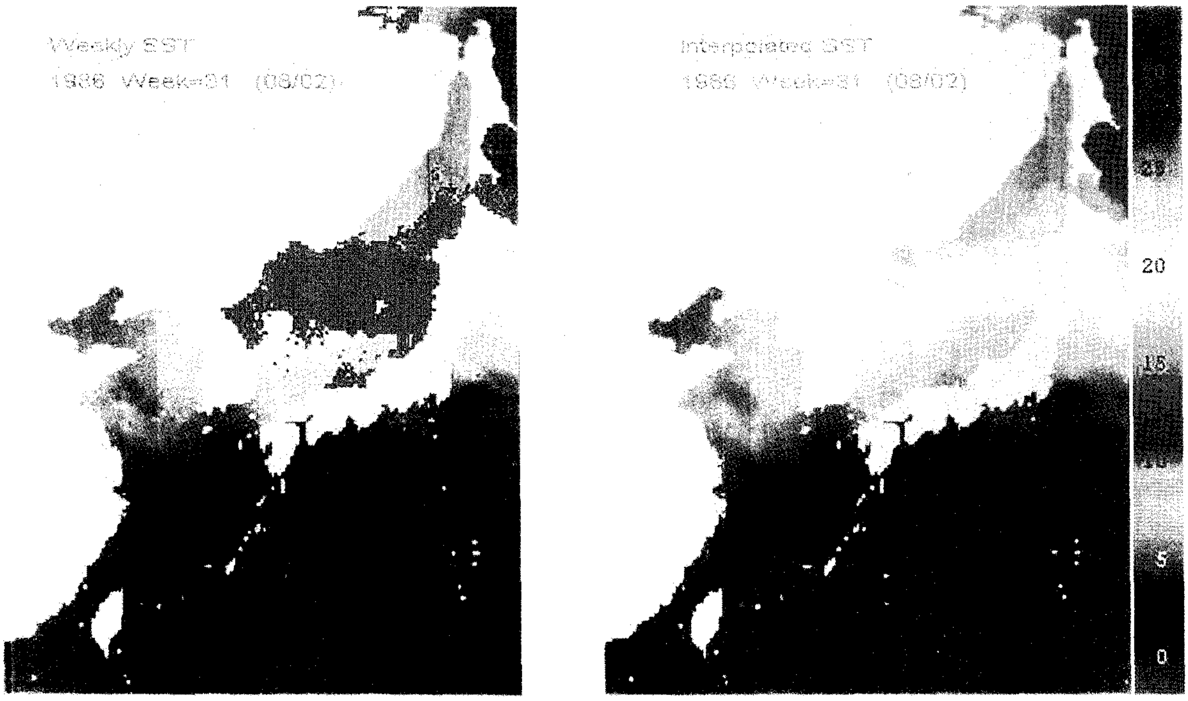

Fig. 3. Obsered (left) and interpolated SST (right) at 31st week (August) of 1986. Erroneous data or cloud covered areas are shown by grey color.

using time series modelling.

3. The satellite remote sensing SST data

The SST data we used are the NOAA/NASA AVHRR weekly data in the region of 115-145°E and 20-55°N. The spatial sampling interval is 0.175781 degrees (approximately 20 km). We used weekly SST data for 18 years from 1981 to 1998. Number of sea grid with SST data in on our study area is 18197. This data set is archived by Korea Ocean Research and Development Institute through the internet download from NOAA/NASA.

The archived data contain interpolated data which are not physically acceptable. The erroneous data are discarded as follows. We computed weekly SST normals and anomalies for 18 years from the data set. If the magnitude of SST anomalies is larger than 12℃, we treated that data as missing data. We computed again the SST normals and anomalies using data excluding missing data, and applied the similar but more stringent data rejection criterion of SST anomalies larger than 10℃. This kind of operation is successively applied 13 times by reducing SST anomaly limit (final smallest limit of SST anomaly was set to 3℃). The missing data are interpolated by linear interpolation of SST anomalies.

SST normals in February and August in our study area are shown in Fig.1. Fig. 2 shows the observed and interpolated SST anomalies in early August of 1986, as an example. Fig. 3 shows the observed and interpolated SST, which are made by superposition of SST anomalies and SST normals.

4. Seasonal variation of SST

We computed 52 weekly normals of SST for 18 years at 18197 locations. The weekly SST normals $T_{nor}(t)$ at each location are fitted to a harmonic function

$$T_{nor}(t) = T_0 + A_1\cos(\omega t-\phi_1) + A_2\cos(2\omega t-\phi_2),$$

where T_0 is average, A_1 and A_2 are annual and semi-annual amplitudes, respectively, ϕ_1 and ϕ_2 are annual and semi-annual phases, respectively, and ω is annual angular frequency (Kang and Jin 1984).

Fig. 4. Annual averages of SST.

Fig. 4 shows the spatial distribution of annual averages of SST. Annual averages of SST in the Kuroshio region are higher than 20 ℃ and those in the northern part of East Sea are less than 10 ℃. Fig. 5 shows the annual amplitudes and phases of seasonal SST variations. The annual amplitudes of SST in the Kuroshio region are less than 5 ℃ and those in the northern part of the Yellow Sea are larger than 10 ℃. The distribution of annual phase of SST shows that the maximum temperatures in the regions far away from the coast occurs at the end of August, but those in the coastal region of the Yellow Sea occur at the end of July.

5. Time series modelling of SST anomalies

The root mean square (RMS) amplitudes of SST anomalies are typically of an order of 1 ℃. In the frontal regions, however, they exceed more than 1 ℃. The time scales of SST anomalies are estimated by time interval between the change of sign of SST at each location. The average days elapsed in the change of SST anomaly signs in our study area are 28.3 ±3.8 days, indicating that the SST anomalies are rather persistent with time scales of 1 month.

Utilizing the persistency of SST anomaly, we applied Markov process model or auto-regression of order 1 model AR(1) to the time series of SST anomalies at each location by the equation

$$T_i = \phi_i T_{i-1} + a_i ,$$

where T_i and T_{i-1} are SST at time i and i-1, respectively, and a_i is a random noise. The AR(1) coefficient ϕ_1 can be estimated by (Mardakis and Wheelwright 1979)

$$\phi_1 = \frac{\sum_{i=2}^{n} T_i T_{i-1}}{\sum_{i=2}^{n} T_{i-1}^2} .$$

Fig. 6 shows the predicted and observed SST anomalies at 20th week (May) of 1984, as an example. The SST is predicted by adding the predicted SST anomaly to the SST normal. Fig. 7 shows the predicted and observed SST at 20th week (May) of 1984.

The AR(1) coefficients represent the degree of thermal inertia or 'memory' of the SST anomaly. The AR(1) coefficients have tendency to decrease with an increase of prediction period. The AR(1) coefficients of weekly SST anomalies at 18197 locations are 0.640 ±0.131. That is, the memory effect in the variance of the SST anomaly for 1 week is 64%. The AR(1) coefficients of daily SST at Marado in Cheju Island was 0.9998, and that for bimonthly SST at 175 Stations around Korea by the Fisheries Research and Development Institute was 0.23 (Kang *et al.* 1991). The different AR(1) coefficients for daily and bimonthly SST data indicate that the memory of SST anomalies decays with time.

The variance σ_a^2 of unpredictable random noise is given by

$$\sigma_a^2 = \frac{1}{N-1} \sum_{i=2}^{n} (T_i - \phi_i T_{i-1})^2 .$$

The RMS of the unpredicted SST anomalies by Markov model fit is 0.88 ±0.79 ℃. Compared to the RMS of the SST anomalies themselves of 1.13 ±0.76 ℃, the Markov model fit reduces the prediction error by 0.25 ℃.

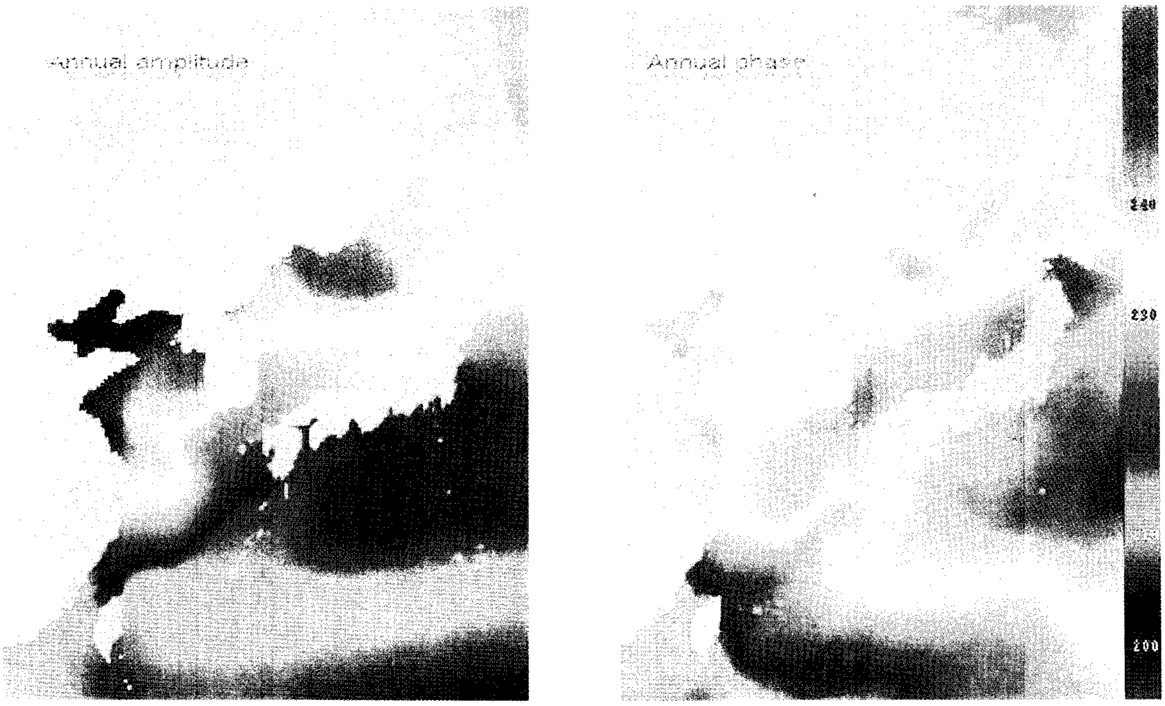

Fig. 5. Annual amplitudes (left) and phases of SST (right).

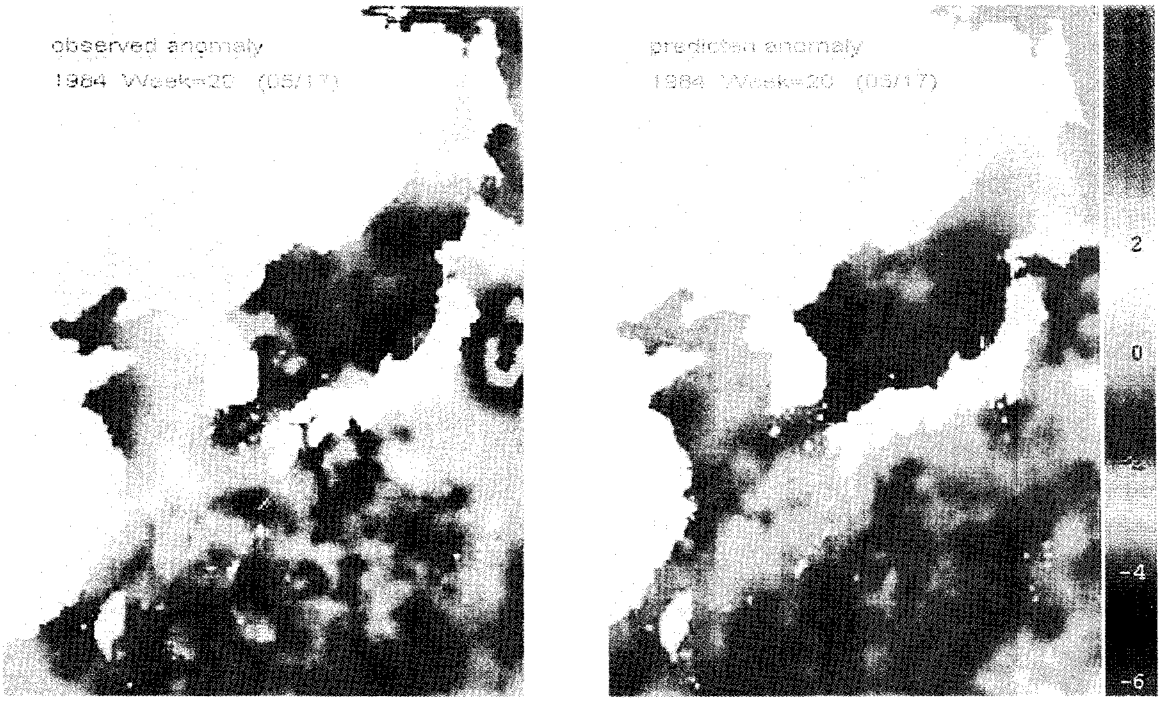

Fig. 6. Observed SST anomalies (left) and interpolated SST anomalies (right) at 20th week (May) of 1984.

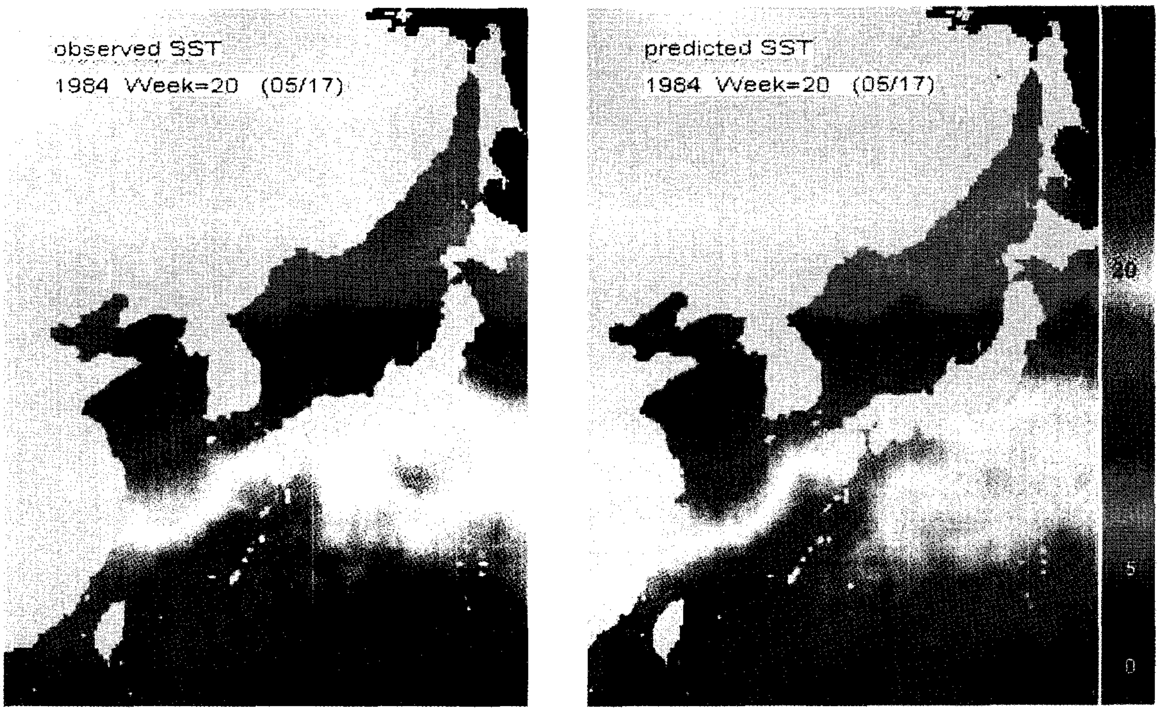

Fig. 7. Observed SST (left) and interpolated SST (right) at 20th week (May) of 1984.

6. Conclusion

For model calibration and data assimilation of real time three-dimensional circulation model, the satellite remote sensing SST data are very useful. Although we can get real time SST image by NOAA AVHRR up to 6 times per day, we cannot get SST data in cloud region. The SST prediction technique described in this paper can be used for nowcast of SST in cloud region. Since the accuracy of SST prediction decreases with the length of prediction time, our method is applicable for short range prediction only. The real time NOAA SST images are received and archived at several stations in Korea such as Korea Ocean Research and Development Institute, National Fisheries Research and Development Institute, and Ocean Research Institute in Seoul National University. Nowcast of SST in cloud region and forecast of short range SST, which is very needed for the real time three-dimensional circulation model, can be provided by applying time series modelling of satellite remote sensing SST data.

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