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博 士 論 文

Ocean surface emissivity modeling in microwave radiance
assimilation for numerical weather prediction

(数値天気予報のためのマイクロ波放射輝度同化における
海面射出率のモデル化)

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Abstract

Accurate initial fields are essential for numerical weather prediction (NWP). Various observational data (e.g., ground-based *in situ* data, upper air sounding data, and remote sensing data) are assimilated to produce the initial fields. Satellite radiance data are among the most important observations, especially over areas where conventional observations are limited (e.g., ocean areas). In this thesis, the impact of direct assimilation of satellite radiance on NWP forecasts is examined. Furthermore, new ocean emissivity models are developed to extract ocean surface information effectively in radiance assimilation. These studies prove that the use of radiance data and microwave ocean emissivity models in data assimilation substantially improves NWP forecast accuracy and benefits weather forecasting.

There are two approaches to the assimilation of satellite data. One is “retrieval assimilation” in which the assimilation is of geophysical parameters such as temperature and humidity retrieved from observed radiance data. The other is “radiance assimilation” in which observed radiance data are directly assimilated. In global data assimilation, direct radiance assimilation is the mainstream among operational NWP centers. However, in regional data assimilation, the method of radiance assimilation has not been established because of difficulties in estimating biases in simulated radiances within limited regions and time periods.

For the first study of this research, a satellite radiance assimilation scheme for the Japan Meteorological Agency (JMA) operational mesoscale NWP system was developed and its impact on analyses and forecasts was examined. Estimated biases of the radiance data in the JMA global analyses were used for bias correction in the mesoscale analysis. Experiments comparing radiance assimilation and retrieval assimilation in the mesoscale NWP system were conducted. These experiments demonstrated increased availability of satellite radiance data in the analyses and improvements to the tropospheric geopotential height forecasts and precipitation forecasts. The improvements resulted from the introduction of radiance data from multiple satellites into data-sparse regions and time periods. Based on these results, direct radiance assimilation is now used in the JMA operational mesoscale analysis.

In the second study, the impact of radiance observations from the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) on the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) was investigated. The GDAS used NCEP’s Gridpoint Statistical Interpolation (GSI) analysis system and the operational NCEP global forecast model. To improve the performance of AMSR-E low-frequency channels’ assimilation, a new microwave ocean emissivity model and its adjoint model with respect to the surface wind speed and temperature were developed and incorporated into the assimilation system. The most significant impacts of AMSR-E radiance data on the analysis were an increase in temperature of about 0.2 K at 850 hPa at higher latitudes and

a decrease in humidity of about 0.1 g kg^{-1} at 850 hPa over the ocean when the new emissivity model was used. There was no significant difference in the mean 6-h rainfall in the assimilation cycle. Forecasts made from the assimilation that included AMSR-E data showed small improvements in the anomaly correlation of geopotential height at 1000 and 500 hPa in the Southern Hemisphere and reductions in the root-mean-square error (RMSE) for 500 hPa geopotential height in the extra-tropics of both hemispheres. Use of the new emissivity model resulted in improved RMSE for temperature forecasts from 1000 to 100 hPa in the extra-tropics of both hemispheres. Assimilation of AMSR-E radiance data that used the emissivity model improved the track forecast for Hurricane Katrina in the 26 August 2005 case, whereas assimilation that used the NCEP operational emissivity model, FAST microwave Emissivity Model (FASTEM) version 1, degraded it.

For the third study, an empirical relative wind direction (RWD) model function was developed to represent the azimuthal variations of oceanic microwave radiances of the vertical and horizontal polarizations. The RWD model function was based on radiance measurements from the Advanced Microwave Scanning Radiometer and Special Sensor Microwave Imager/Sounder (SSMIS). Ocean surface wind vector data from the SeaWinds instrument on board the Advanced Earth Observing Satellite-II and the European Centre for Medium-range Weather Forecasts (ECMWF) Integrated Forecasting System were used for the development of the RWD model function. The RWD model function was introduced to FASTEM in a radiative transfer model for satellite radiance assimilation. Performance of the RWD model function was much more realistic than present azimuthal model functions in FASTEM for low wind speed and high-frequency channels. Assimilation experiments using the RWD model function were performed in the ECMWF system. The experiments demonstrated reductions of first-guess departure biases arising from modeling of the azimuthal variations in areas of high wind speed and low variability of wind direction. Bias reductions in the ascending and descending SSMIS 19 GHz vertically polarized radiance in the Somali jet over the Arabian Sea were approximately 0.6 and 0.7 K, respectively. Bias reductions were found for all assimilated microwave imager channels over a wide wind-speed range. Moreover, analysis increments of specific humidity in the lower troposphere were reduced (e.g., 0.2 g kg^{-1} reduction at 1000 hPa in the Somali jet). Improvements in relative humidity and temperature were found in short-range forecasts in the lower troposphere. The experimental results clearly showed the importance of modeling the azimuthal variation of emissivity for assimilation of microwave imager observations. The new RWD model function, combined with the other components of FASTEM, is available as FASTEM-6.

The contributions of this thesis toward the progress of microwave radiance data assimilation for NWP models are as follows: (i) Extension of microwave radiance assimilation to regional models. This is an important progress of the satellite data assimilation for regional models because the contribution of satellite data to the accuracy of analyses and forecasts is greater than that of the previous retrieval assimilation stage. (ii) Development of two microwave ocean emissivity models to extract ocean surface information from microwave radiance through the data assimilation process. The target information is surface wind speed and wind direction. The information was successfully extracted by ocean emissivity modeling of the microwave

radiance variation. Moreover, the use of emissivity models together with microwave radiance observations in data assimilation leads to substantial improvement in NWP forecast accuracy. This is evidence that the ocean emissivity model can represent the variation of microwave radiance caused by meteorological conditions.

From a practical perspective, this thesis contributes to the improvement in accuracy of operational weather forecasting. The results of the first study are implemented in the JMA operational mesoscale system, which has been in use since December 2010. The two emissivity models are implemented in U.S. and European global data assimilation systems for operational weather forecasting. Furthermore, the emissivity models are included in two major radiative transfer model packages. The emissivity models developed in this research are used by present operational NWP centers and radiance data assimilation scientists around the world.

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1. General Introduction

1.1. Numerical Weather Prediction and Data Assimilation

This thesis describes research performed to improve weather forecasting. Numerical Weather Prediction (NWP) is an approach to weather forecasting in which forecasts are produced with mathematical atmospheric models and information on the present status of the atmosphere and surface of the earth. The present status is referred to as the initial conditions for NWP models. To calculate the future state of the atmosphere and surface, atmospheric NWP models use the following physical laws to describe the evolution of the atmosphere: conservation of momentum, the equation of continuity, the equation of state for ideal gases, conservation of energy, and conservation of water mass. These partial differential equations are solved with numerical discretization and parameterized physical processes on the sub-grid scale (e.g., the radiation process and the cloud and precipitation process). Therefore, it can be said that NWP is a procedure for solving an atmosphere and surface initial value problem numerically.

In weather forecasting, the future states of meteorological variables such as temperature, humidity, wind vector, and surface pressure are simulated with NWP models by using high-performance computers (supercomputers) to obtain high resolution. The NWP forecasts are produced not only for research purposes (studying on a specific meteorological phenomenon) but also for operational purposes (daily weather forecasting and issuing severe weather warnings). At operational NWP centers around the world, various NWP global and regional models are run in real time. The output of NWP models of meteorological variables is crucial information for present-day weather forecasting. These variables play a critical role in decisions regarding the issuance of weather warnings for severe weather events such as heavy precipitation caused by a seasonal front, tropical cyclones, and typhoons.

For accurate prediction of these meteorological phenomena with NWP models, realistic initial fields for NWP models are necessary. Data assimilation can produce accurate initial fields by using first-guess fields from short-range forecasts by an accurate NWP model and various real observation data. Direct measurements of the meteorological variables, such as temperature and humidity profiles from radio-sonde observations, surface pressure, and wind vectors from meteorological observation stations and oceanic buoys, have been used in data assimilation. These are called conventional observations, and these *in situ* measurements are high-quality observation data. However, the available coverage areas of the data are limited spatially and temporally. For example, normally radio-sonde sounding observations are performed at 00 and 12 UTC and are limited to certain land areas or small island stations. To the contrary, remote sensing data (e.g., radar and satellite observations) are indirect measure-

ments of meteorological variables. To obtain these meteorological variables, an inversion process is necessary. Such retrievals of temperature, humidity, precipitation, atmospheric wind vectors, and atmospheric water vapor have been used in data assimilation for NWP forecasts. At present, the key observation in data assimilation for NWP models is of satellite data. In general, satellite data have global coverage from space-based measurements and uniform data quality from single sensor measurements. In recent years, the importance of satellite observation in data assimilation has increased. For accurate production of the initial conditions, utilization of satellite data is an essential part of operational data assimilation. Introduction of new satellite data and development of enhanced uses of satellite data are important tasks for operational NWP centers. Moreover, the results of scientific research on satellite data utilization must be used to improve NWP forecasts.

Variational Data Assimilation

Modern NWP centers use variational methods for data assimilation. Three/four-dimensional variational data assimilation (3D-Var/4D-Var) approaches are used in their operation systems and are strong tools for extracting meteorological information from observations and producing the initial fields for NWP models. 4D-Var produces the analysis field as a time evolution of an NWP model that is close to all observations and first-guess fields from the NWP model in the assimilation time window. The estimated analysis field at the initial time is used as the start for the NWP model to simulate the future state.

Because 4D-Var employs physical laws represented by the NWP model to produce the initial conditions for data assimilation, the amount of extracted observation information is much larger than that of 3D-Var data assimilation. 3D-Var assumes that all observation times are the same as the analysis time. Because 4D-Var can assimilate non-periodic observations at the observed times during the assimilation time window, it is suitable for assimilating continuous observation data like polar-orbiting satellite data.

A key process in variational data assimilation is finding the best field that is close to the observation values and forecast model's first-guess value by considering both observation errors and forecast model errors. To measure the distance from the observation and the first guess, a cost function J is defined. This cost function is minimized in the data assimilation procedure.

Cost Function J

In 3D-Var data assimilation, the cost function is defined as follows:

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}^b) + \frac{1}{2}(\mathbf{H}\mathbf{x} - \mathbf{y}^o)^T \mathbf{R}^{-1}(\mathbf{H}\mathbf{x} - \mathbf{y}^o) \quad (1.1)$$

where $\mathbf{B}$ is the background error covariance matrix, $\mathbf{R}$ is the observational error covariance matrix, $\mathbf{x}$ is the analysis vector, $\mathbf{y}^o$ is observation data vector (e.g., satellite radiance data), and $\mathbf{x}^b$ is the background vector (normally obtained from a short-range forecast). H is an observation operator that transforms analysis variables into observation space. H is composed of

horizontal and vertical interpolations from NWP model grid space to the observation location. In addition, in the case of satellite radiance, the radiative transfer calculation is included in the H operator.

To find the optimal initial field for NWP models, minimization of the cost function J is performed. The analysis field $\mathbf{x}_a$ is given as a solution of

$$\nabla_{\mathbf{x}} J(\mathbf{x}_a) = 0. \quad (1.2)$$

To find the gradient of the cost function, a small variation of J in terms of the analysis vector $\mathbf{x}$ is considered:

$$\begin{aligned} \delta J = & \frac{1}{2} \delta \mathbf{x}^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}^b) + \frac{1}{2} (\mathbf{x} - \mathbf{x}^b)^T \mathbf{B}^{-1} \delta \mathbf{x} \\ & + \frac{1}{2} (\mathbf{H} \delta \mathbf{x})^T \mathbf{R}^{-1} (H\mathbf{x} - \mathbf{y}^o) + \frac{1}{2} (H\mathbf{x} - \mathbf{y}^o)^T \mathbf{R}^{-1} \mathbf{H} \delta \mathbf{x}, \end{aligned} \quad (1.3)$$

where $\mathbf{H}$ is defined as

$$\mathbf{H} = \frac{\partial H}{\partial \mathbf{x}}. \quad (1.4)$$

The matrix elements can be expressed as $H_{ij} = \partial H_i / \partial x_j$. In the case where there is a radiative transfer calculation in the observation operator, suffix i indicates the sensor channel number and suffix j indicates the inputs (i.e., temperature, humidity, and ozone). Matrix $\mathbf{H}$ is a tangent linear operator of the observation operator H in terms of $\mathbf{x}$ and is called the Jacobian matrix. By using the symmetric character of matrices $\mathbf{B}$ and $\mathbf{R}$, equation (1.3) can be written as follows:

$$\delta J = \delta \mathbf{x}^T [\mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}^b) + \mathbf{H}^T \mathbf{R}^{-1} (H\mathbf{x} - \mathbf{y}^o)]. \quad (1.5)$$

Then, the gradient of the cost function J can be expressed as

$$\nabla_{\mathbf{x}} J = \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}^b) + \mathbf{H}^T \mathbf{R}^{-1} (H\mathbf{x} - \mathbf{y}^o), \quad (1.6)$$

where $\mathbf{H}^T$ is the transpose of matrix $\mathbf{H}$ and is called the adjoint operator of the tangent linear operator.

In 4D-Var data assimilation, the formulation is written as an extension of the 3D-Var case:

$$J(\mathbf{x}_0) = \frac{1}{2} (\mathbf{x}_0 - \mathbf{x}_0^b)^T \mathbf{B}^{-1} (\mathbf{x}_0 - \mathbf{x}_0^b) + \frac{1}{2} (H\mathbf{M}\mathbf{x}_0 - \mathbf{y}^o)^T \mathbf{R}^{-1} (H\mathbf{M}\mathbf{x}_0 - \mathbf{y}^o), \quad (1.7)$$

where M represents a time evolution operator defined with the NWP model and $\mathbf{x}_0$ is a vector of the analysis variables at the beginning ($t = 0$) of the assimilation time window.

As described above, in the case of radiance assimilation, H and $\mathbf{H}$ include the radiative transfer calculation in the observation operator. H is the forward model calculation (transforming the analysis variables to radiance) and Jacobian matrix $\mathbf{H}$ expresses the radiance sensitivity of the meteorological variables (temperature, humidity, ozone, etc.). The radiative transfer models used for the radiance assimilation in this research are introduced in Chapter 2.

Variational Bias Correction

In variational data assimilation, it is assumed that there is no bias in the forecast model or observations. In reality, however, various biases exist in both the forecast model and observations. To correct for the biases adaptively, analysis variables (control variables in data assimilation) can be extended with several predictors for the bias correction. The biases are described as polynomial functions with predictors whose coefficients are optimized during the minimization of the cost function. This method is called variational bias correction (VarBC; Dee, 2004) and is applied to radiance data assimilation. The VarBC method is widely used in global data assimilation at operational NWP centers.

1.2. Space-based Microwave Radiance Observation

To improve weather forecasting, improvement of the NWP model itself and realistic initial fields are required. The observations used in data assimilation that produce the initial fields of the NWP model are extremely important. Microwave observations contain rich information on various geophysical parameters. Use of this information strongly benefits the accuracy of the analyses and forecasts in NWP. Therefore, microwave radiance assimilation is a key element in data assimilation. Information on the amount of water vapor in the atmosphere determines the accuracy of precipitation forecasts. Microwave radiometer data provide atmospheric water vapor information with wide coverage under clear and cloudy conditions. It is thought that microwave imager data assimilation can substantially improve precipitation forecasting.

Space-based microwave radiance observations have become an indispensable part of the global Earth Observing System (EOS). In data assimilation for NWP forecasts, the information obtained from microwave imagers helps improve atmospheric humidity, cloud, and precipitation analyses and forecasts. Operational NWP centers have been using information from radiance data from the Defense Meteorological Satellite Program (DMSP) satellite Special Sensor Microwave Imager Sounder (SSMIS) (Kunkee et al., 2008; Bell et al., 2008), the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) (Kummerow et al., 1998), and the Aqua Advanced Microwave Scanning Radiometer for EOS (AMSR-E) (Kawanishi et al., 2003) for global data assimilation (Bauer et al., 2006a,b; Treadon et al., 2002). Further developments and enhancements are in progress (Bauer et al., 2011). Space-based remote sensing observation has various advantages compared to *in situ* measurements. For instance, global observation is available with a single instrument. Furthermore, an important characteristic of microwave radiance is that the atmosphere is transparent to the radiation. Therefore, the observation of microwave radiance can provide information under cloudy and rainy conditions.

In this research, various microwave imagers are utilized (e.g., AMSR, AMSR-E, SSMIS, and TMI). The AMSR instrument is available together with a scatterometer (SeaWinds). Simultaneous measurements of radiance and surface wind are available for a limited period (seven months). This data set is used in Chapter 5 to estimate the variation of oceanic mi-

microwave radiance related to the relative wind direction under high surface wind conditions. The AMSR-E data are used for radiance data assimilation in Chapter 4, and SSMIS and TMI are used operationally in radiance assimilation at many NWP centers. In Chapter 5, a radiance data assimilation system that includes these microwave imager data is used for data assimilation experiments.

In recent decades, satellite observations have been used in global data assimilation at NWP centers. Radiance assimilation in global data assimilation is well established and observational information on temperature and humidity from radiance data is extracted through the radiative transfer model in the data assimilation. However, there are unexplored scientific issues in the use of microwave radiance. In regional data assimilation, the impact of direct radiance assimilation has not yet been fully investigated because of several difficulties in dealing with the radiance simulations in a regional model with a limited model-top height and their bias corrections in operational NWP systems. To begin the study, the impact of radiance assimilation on a regional NWP system must be investigated. This study is very important for improving NWP forecasting skill.

In radiance data assimilations for NWP forecasts, the present assimilation of microwave imagers is not optimal for extracting radiance observation information. The channels used are limited to the Ku, K, Ka, and W bands. Low-frequency channels (C and X bands, i.e., the 6 and 10 GHz channels of AMSR-E and AMSR2) are not assimilated at any operational NWP centers. The scientific impact of the radiance data assimilation of low-frequency channels is unknown. Observations from these channels are rich in surface information because the 6 and 10 GHz channels are less affected by hydrometeors in the atmosphere. They contain not only water vapor information but also surface information (sea surface wind and temperature) under cloudy and rainy conditions. Although retrieval products from low-frequency channels exist, this surface information has not yet been utilized in radiance data assimilation. To make use of the radiance data from low-frequency channels, an accurate ocean surface emissivity model for the radiative transfer calculation is necessary.

Sea surface wind speed information from the NWP first-guess field is used for the simulation of microwave radiance as an input to the ocean surface emissivity model. Wind speed information for the observed radiance is reflected in the atmospheric analysis through data assimilation. However, microwave radiance data, especially microwave imager measurements, contain not only surface wind speed information but also surface wind direction signals. As shown in several studies obtained in geophysical retrievals, the azimuthal variation of microwave imager radiance observations reaches about 2 K in high wind-speed conditions. This phenomenon should be taken correctly into account in the calculation of microwave ocean emissivity for the radiance assimilation. Otherwise, the azimuthal variation may cause incorrect increments or excessive data rejection in the data assimilation, especially under strong wind conditions. Furthermore, short-range forecasting accuracy has increased significantly in recent years, so errors arising from neglecting the azimuthal variation of radiance in the radiative transfer calculation are increasingly significant. Therefore, the effect of the azimuthal variation on microwave radiance assimilation should be explored. To perform this investigation, an ocean surface emissivity model should be developed to represent the azimuthal

variation realistically.

1.3. Research Motivation and Scope of this Thesis

To improve the accuracy of NWP forecasts, observation information should be properly reflected in the initial field. Various observational data are assimilated to produce the initial field for NWP forecasts. In this research, the impact of satellite radiance on the analyses and NWP forecasts is examined in depth. In particular, radiance data from microwave imagers are focused upon and ocean emissivity models in the radiative transfer calculation are developed. At present, surface information in microwave imager radiances is not fully extracted in data assimilation; therefore, the development of an improved ocean emissivity model is necessary. Furthermore, data assimilation experiments should be performed to investigate the impact of the use of radiance data and the ocean emissivity model on the accuracy of NWP forecasts.

Historically, the use of satellite data began with retrieval data. The retrieval data are parameters commonly used in meteorology: temperature profiles, humidity (total precipitable water), precipitation, and surface properties (surface wind speed and surface temperature). Moreover, temperature and humidity are basic control variables in data assimilation. The use of these retrievals is straightforward and, in fact, these retrieval data have been used in data assimilation by contributing to the creation of accurate initial fields for NWP models. However, the use of retrieval products has some weaknesses. To retrieve geophysical parameters from satellite observations (e.g., radiance), physical or statistical algorithms are necessary. Generally, such algorithms have errors and limitations on their accuracy and applicable range. Moreover, development and tuning of the algorithms for the retrievals typically requires a time period of several months to years. With regard to operational data use, these are deficiencies in the retrieval products. To overcome these deficiencies, a direct radiance assimilation approach is taken at operational NWP centers. For global data assimilation, direct radiance assimilation is mainstream. However, for regional data assimilation, the method of direct radiance assimilation has not yet been established because of the difficulties in the treatment of satellite radiance bias and the radiative transfer calculation. In the first study, the impact of radiance data assimilation on a regional model was examined. The study was performed by using a mesoscale NWP system at the Japan Meteorological Agency. In radiance assimilation, microwave data play a dominant role in producing accurate initial fields for the NWP model. The results of the first study prove the importance of microwave radiance assimilation for the accuracy of the initial field for the NWP model and improved precipitation forecasts.

The second study was of the impact of AMSR-E radiance data assimilation on obtaining more information from microwave imager measurements. For data assimilation of low-frequency channels, a new ocean emissivity model was developed. The biases that depend on the surface wind speed should be small to extract surface wind information in the data assimilation. The AMSR-E radiance assimilation with the new ocean emissivity model improved a hurricane track prediction. The data assimilation experiments were performed by using the NCEP global data assimilation system.

Microwave imagers obtain values of various geophysical parameters related to atmospheric humidity and ocean surface wind. In the third study, ocean surface wind direction information was considered in the modeling of ocean surface emissivity. The enhanced ocean surface emissivity model was developed with simultaneous measurements of radiance and surface wind vectors by the ADEOS-II satellite. The developed ocean emissivity model was introduced in a global data assimilation system. The assimilation of microwave imager radiance data under all-sky conditions together with the new ocean emissivity model should improve analyses and forecasts. The wind directional signal in microwave imager measurements should be properly assimilated with the new ocean emissivity model. The data assimilation experiments were performed by using the ECMWF global data assimilation system.

Chapter 2 describes the key concepts of microwave radiance assimilation relevant to this research. The following three chapters present the three studies on microwave radiance assimilation. In Chapter 3, the radiance assimilation system for the JMA mesoscale NWP system is developed and the impact on NWP forecasts is investigated. In Chapter 4, an improved ocean emissivity model for low-frequency microwave channels is developed and the impact of AMSR-E radiance data on the NCEP global data assimilation system with the ocean emissivity model is studied. In Chapter 5, an improved ocean emissivity model that represents the relative wind direction effect under high surface-wind conditions is developed and its impact on NWP forecasts is investigated in the ECMWF data assimilation system. These three studies demonstrate the importance of microwave radiance data assimilation and the use of accurate microwave ocean emissivity to extract surface wind information in data assimilation for NWP forecasts. Chapter 6 provides a summary of this research and conclusion, including the future prospects of microwave radiance data assimilation and ocean emissivity modeling.

2. Satellite Microwave Radiance Assimilation

2.1. Microwave Radiative Transfer

In this section, several basic concepts regarding microwave radiative transfer in the atmosphere are introduced for this study. General overview of microwave radiative transfer is discussed in literature on remote sensing (e.g., Janssen, 1993; Liou, 2002). In this study, clear sky (i.e., no clouds and no scattering) radiative transfer is considered for satellite microwave radiance assimilation. In microwave radiative transfer in a clear sky atmosphere, water vapor and oxygen molecules exhibit dominant absorption of the radiation. The microwave radiation region is generally defined as a frequency range from 300 to 0.3 GHz, which corresponds to an electromagnetic wave wavelength of 1 mm to 1 m. There are dominant water vapor absorption lines at 22.235 GHz and 183 GHz in the microwave spectrum range. The oxygen molecule has a strong absorption band near 60 GHz and a single absorption line at 118.75 GHz. Except for these absorption lines, the atmosphere is relatively transparent in the microwave spectrum range.

Traditionally, measurements of microwave radiation from space have been performed at the following frequencies: 1.4, 6, 10, 18, 21, 37, 55, 90, 157, and 183 GHz. These frequencies are chosen at the near peak of the absorption lines to obtain temperature and water vapor sounding information. In addition, they are chosen between the peaks to obtain imaging information from the surface with less attenuation of the microwave radiation. Channels near the 22 GHz water vapor absorption line provide important measurements for determining the amount of water vapor in the atmosphere. Channels between 50 to 70 GHz are used for temperature sounding purposes. Channels near 183 GHz are suitable for water vapor sounding in the troposphere. Other window channels have been used to monitor the earth's surface condition (e.g., sea surface temperature, sea surface wind, soil moisture, sea ice distribution, and snow cover). Microwave radiation can penetrate clouds and light rains. Therefore, the measurements can provide detailed information regarding the geophysical parameters of water vapor, temperature and the earth's surface under all weather conditions. The information obtained using from microwave radiance measurements from space is important for environment monitoring and data assimilation for NWP.

The general radiative transfer equation is described as a differential form as follows:

$$\frac{dI_\nu}{ds} = -\beta_e I_\nu + S, \quad (2.1)$$

where I_ν describes the intensity of radiation, β_e is an extinction coefficient, S is a source term of radiation, and ν is frequency of microwave radiation. On the equation's right-hand side, the first term denotes the extinction of the radiation while the second term denotes the emission of radiation through a layer of air with infinitesimal thickness ds . The direction of the radiation is described by s . Because no scattering is assumed in the atmosphere in this research, the extinction coefficient β_e becomes equal to an absorption coefficient β_a .

Generally, the assumption of a local thermodynamic equilibrium in the tropospheric atmosphere is valid. Based on Kirchhoff's law, the source term is described with the Plank function $B_\nu(T)$ as follows:

$$S = \beta_a B_\nu(T), \quad (2.2)$$

where $B_\nu(T)$ is expressed as follows:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1}, \quad (2.3)$$

where h is Plank's constant, k_B is Boltzmann's constant, c is the speed of light, ν is the frequency, and T is physical temperature. The radiative transfer equation for no scattering medium is as follows:

$$\frac{dI_\nu}{ds} = -\beta_a I_\nu + \beta_a B_\nu(T). \quad (2.4)$$

This fundamental equation is known as Schwarzschild's equation.

The solution of the radiative transfer equation for a clear sky atmosphere in local thermodynamic equilibrium is obtained by the integration of equation (2.4),

$$I_\nu(0) = I_\nu(s_0)e^{-\tau(s_0)} + \int_0^{s_0} B_\nu(T)e^{-\tau(s)} \beta_a(s) ds, \quad (2.5)$$

where τ is the optical depth and defined as follows:

$$\tau(s) \equiv \int_0^s \beta_a(s') ds'. \quad (2.6)$$

By using the Rayleigh-Jean approximation ($h\nu \ll k_B T$) for microwave radiation, the Plank function is approximated as follows:

$$B_\nu(T) \approx \frac{2\nu^2 k_B T}{c^2} = \frac{2k_B T}{\lambda^2}, \quad (2.7)$$

where λ is the wavelength of the radiation. The microwave brightness temperature can be defined as follows:

$$T_b(\nu) \equiv \frac{\lambda^2}{2k_B} I_\nu. \quad (2.8)$$

It is assumed that the physical temperature T of a black body is equal to its brightness temperature $T_b(\nu)$. In this case, the Rayleigh-Jeans approximation expressed as equation (2.7) is incorporated.

The radiative transfer equation for microwave radiation is described with the brightness temperature as follows:

$$T_b(\nu) = T_{b0} e^{-\tau(s_0)} + \int_0^{s_0} T(s) e^{-\tau(s)} \beta_a(s) ds, \quad (2.9)$$

where T_{b0} is the background brightness temperature defined with the following boundary condition:

$$T_{b0} = \frac{\lambda^2}{2k_B} I_\nu(s_0). \quad (2.10)$$

In the case of a microwave imager measurement, microwave radiation is measured with a local zenith angle θ . The angle θ is defined as the angle between the normal direction (z-direction) from the earth's surface and the direction of the radiation. Slant path s in the radiation direction and the angle θ are related as follows:

$$s = z \sec \theta. \quad (2.11)$$

The optical depth τ can be expressed in the vertical coordinate as follows:

$$\tau(\nu, z) = \int_z^H \beta_a(\nu, z') dz', \quad (2.12)$$

where H is the satellite altitude, and $z = 0$ means the earth's surface. Using the relationship (2.11), the microwave radiative transfer equation (2.9) can be written as follows:

$$T_b(\nu, \theta) = T_{b0} e^{-\tau(\nu, 0) \sec \theta} + T_u(\nu, \theta), \quad (2.13)$$

and

$$T_u(\nu, \theta) = \sec \theta \int_0^H T(z') \beta_a(\nu, z') e^{-\tau(\nu, z') \sec \theta} dz'. \quad (2.14)$$

Equation (2.14) indicates the up-welling radiation term in the microwave radiative transfer equation. The brightness temperature T_{b0} expressed as the boundary term consists of two components. One is the surface-emitted radiation T_e . The other is the reflected radiation of the down-welling radiation at the surface T_r . Equation (2.13) can be described as follows:

$$T_b(\nu, \theta) = T_u(\nu, \theta) + T_e(\nu, \theta) e^{-\tau(\nu, 0) \sec \theta} + T_r(\nu, \theta) e^{-\tau(\nu, 0) \sec \theta}. \quad (2.15)$$

The surface emission radiation T_e is related to surface temperature T_s and surface emissivity ϵ_s as follows:

$$T_e = \epsilon_s(\nu, \theta) T_s. \quad (2.16)$$

The reflected radiation T_r is written from its definition as follows:

$$T_r = [1 - \epsilon_s(\nu, \theta)] T_d(\nu, \theta). \quad (2.17)$$

For the low-frequency range of the microwave spectrum, cosmic background radiation T_c should be considered for the down-welling radiation T_d .

$$T_d(\nu, \theta) = T_c e^{-\tau(\nu, 0) \sec \theta} + \sec \theta \int_H^0 T(z') \beta_a(\nu, z') e^{-[\tau(\nu, 0) - \tau(\nu, z')] \sec \theta} dz'. \quad (2.18)$$

However, for the microwave radiation considered in this research, the effect of the cosmic background term T_c is negligible. Using equations (2.16), (2.17), and (2.18) for equation (2.15), the microwave radiative transfer equation is as follows:

$$T_b(\nu, \theta) = T_u(\nu, \theta) + [\epsilon_s T_s + (1 - \epsilon_s) T_d(\nu, \theta)] e^{-\tau(\nu, 0) \sec \theta}. \quad (2.19)$$

Equation (2.19) is used in a subsequent chapter for surface emissivity estimation based on the observed microwave brightness temperature.

Equation (2.19) can be expressed with a function $S(\nu, P, \theta)$ as follows:

$$T_b(\nu, \theta) = S(\nu, P_s, \theta) T_s - \int_{-\infty}^{\ln P_s} T(P) \frac{dS(\nu, P, \theta)}{d \ln P} d \ln P, \quad (2.20)$$

where $S(\nu, P, \theta)$ is defined as follows:

$$S(\nu, P, \theta) \equiv [1 - (1 - \epsilon_s) e^{-2[\tau(P_s) - \tau(P)] \sec \theta}] e^{-\tau(P) \sec \theta}, \quad (2.21)$$

where P indicates pressure and P_s indicates surface pressure. Thus,

$$S(\nu, P_s, \theta) = \epsilon_s e^{-\tau(P_s) \sec \theta}. \quad (2.22)$$

The optical depth is expressed with pressure coordinates. From hydrostatic relationship,

$$dP = -\rho g dz, \quad (2.23)$$

where g is the gravitational constant, ρ is the density for air. From equations (2.12) and (2.23),

$$\tau(P) = \int_{z(P)}^{z(0)} \beta_a(z) dz = \frac{1}{g} \int_P^{P_s} \frac{\beta_a(z(P'))}{\rho} dP'. \quad (2.24)$$

In equation (2.20), for temperature sounding cases, surface contributions are negligible because $e^{-\tau(P_s) \sec \theta}$ is normally less than 0.1. Equation (2.20) can be approximated as follows:

$$T_b(\nu, \theta) \approx - \int_{-\infty}^{\ln P_s} T(P) \frac{dS(\nu, P, \theta)}{d \ln P} d \ln P, \quad (2.25)$$

and

$$S(\nu, P, \theta) \approx e^{-\tau(P) \sec \theta}. \quad (2.26)$$

Equation (2.26) is a definition of atmospheric transmittance. The weighting function of the integral is expressed as follows:

$$W(\nu, P, \theta) = - \frac{dS(\nu, P, \theta)}{d \ln P}. \quad (2.27)$$

This expression is a definition of the weighting function for microwave radiation. The weighting function depends on the radiation frequency ν , pressure level P , and incidence angle θ .

To perform fast calculations of the radiative transfer in data assimilation, parameterizations of the optical depth τ are necessary. The optical depth is defined in (2.24). For fast radiative transfer calculations, the optical depth is expressed with several predictors and regression coefficients. The transmittance is calculated from the estimated optical depth of the mixing gases (e.g., O_2 and CO_2), water vapor, and ozone. For the microwave spectrum range, water vapor and oxygen molecules are the dominant contributors to optical depth. Atmospheric profiles of temperature, water vapor, and ozone from NWP model outputs are used for the radiative transfer calculation in the data assimilation. In the fast radiative transfer model, the calculation to integrate the up-welling radiance and the down-welling radiance is performed in plane parallel layers that are vertically defined to represent the earth's atmosphere. In the case of surface sensitive radiance, the estimation of surface emissivity ϵ_s is important for the accuracy of simulated microwave radiance. The modeling of surface emissivity for the ocean case is discussed in section 2.3.

2.2. Fast Radiative Transfer Model

Satellite radiance data are currently assimilated at many operational NWP centers primarily by using the variational data assimilation approach (Derber and Wu, 1998; Andersson et al., 1994). Radiance data are among the most important observations for global forecast performance, especially over areas where conventional observations are limited (e.g., the Southern Hemisphere).

To assimilate satellite radiance data, a radiative transfer model is necessary. The radiative transfer model needs to calculate the radiance on top of the atmosphere from atmospheric profiles. Short-range forecasts from numerical prediction models provide the profiles. To use radiance data in variational data assimilation, a forward model for transforming analysis variables into radiance and its adjoint model is required. For simulation of the radiance, fast radiative transfer models have been developed and utilized by operational NWP centers. The two most commonly used fast radiative transfer models are the Radiative Transfer for the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (RTTOV; Saunders et al., 1999) and the Community Radiative Transfer Model (CRTM; Weng, 2007).

2.3. Microwave Ocean Surface Emissivity Model

Microwave radiance measurements from satellites contain information from the atmosphere and the surface. To infer geophysical information from these measurements, an atmospheric radiative transfer model and a surface emissivity model are required. An ocean surface emissivity model is a key element in the radiative transfer model for data assimilation. Since the

1970s, various microwave ocean emissivity models have been suggested. Most of the microwave ocean emissivity models are based on ground-based or aircraft measurements.

Two-scale models of the ocean surface have been suggested by Wu and Fung (1972) and Wentz (1975). These models describe the scattering effect of the ocean surface roughness with sufficient accuracy. However, to calculate the microwave ocean emissivity, two-scale models require integration over the ocean wave spectrum, requiring huge computational resources. Thus, it is difficult to use them in an operational data assimilation system. Therefore, computationally fast ocean emissivity models with sufficient accuracy are necessary for operational data assimilation and NWP.

In the radiance data assimilation community, the FAST microwave Emissivity Model (FASTEM) was developed (English and Hewison, 1998) for the radiative transfer models RTTOV (Saunders et al., 1999) and the Community Radiative Transfer Model (CRTM: Weng et al., 2005). FASTEM is a semi-empirical model that been widely used in many operational NWP centers with the aim of obtaining computationally fast and accurate results. The details of FASTEM are described below.

2.3.1. Microwave Ocean Emissivity in Calm Ocean

A calm ocean surface is characterized by polarized emission. The emissivity can be calculated assuming specular reflection by using the Fresnel equation (e.g., Liou (2002)).

The microwave ocean emissivity can be defined as

$$\varepsilon_p(\nu, \theta) = 1 - \Gamma_p(\nu, \theta), \quad (p = h \text{ or } v), \quad (2.28)$$

where $\varepsilon_p(\nu, \theta)$ is the microwave ocean emissivity, $\Gamma_p(\nu, \theta)$ is the total reflectivity of the ocean surface, p denotes either horizontal (h) or vertical (v) polarization, ν is the radiation frequency, and θ is the incidence angle. Once $\Gamma_p(\nu, \theta)$ is known, the microwave ocean emissivity can be calculated. The emissivity is a function of frequency, polarization, incidence angle, sea-surface temperature, and salinity. In the case of a calm ocean, the ocean surface can be considered to be a specular surface. The Fresnel reflectivity $R_{p,\text{Fresnel}}$ can be computed using Fresnel's law as follows:

$$R_{v,\text{Fresnel}} = \frac{\varepsilon_w \cos \theta - \sqrt{\varepsilon_w - \sin^2 \theta}}{\varepsilon_w \cos \theta + \sqrt{\varepsilon_w - \sin^2 \theta}} \quad \text{and} \quad (2.29)$$

$$R_{h,\text{Fresnel}} = \frac{\cos \theta - \sqrt{\varepsilon_w - \sin^2 \theta}}{\cos \theta + \sqrt{\varepsilon_w - \sin^2 \theta}}, \quad (2.30)$$

where ε_w is the complex dielectric constant (permittivity) of water.

The permittivity (dielectric constant) is one of the basic input parameters for the ocean surface emissivity calculation. Below the microwave frequency region of 20 GHz, the effect of salinity on the permittivity is not negligible. Klein and Swift (1977) presented the permittivity as a function of frequency and water temperature as well as salinity, based on laboratory

measurements. Klein and Swift (1977) used measurements at 1.43 and 2.653 GHz to derive the coefficients of their permittivity model. Their model has sufficient accuracy for the low-frequency range of microwaves and has been used in numerous applications for many years.

However, as several authors have discussed (Meissner and Wentz, 2004; Guillou et al., 1998), the accuracy of the Klein and Swift (1977) model is insufficient beyond the 10 GHz frequency region. Ellison et al. (2003) present an extrapolated model based on a new measurement of permittivity from 20 to 105 GHz. The model of Klein and Swift (1977) uses the single Debye model for low frequencies while the Ellison et al. (2003) model uses the double Debye model for high frequencies to represent the permittivity. Although the double Debye model has not yet been established theoretically, the model well describes the permittivity from 20 to 105 GHz. In FASTEM-1, the Ellison et al. (2003) model is used for the entire microwave frequency range.

2.3.2. Ocean Roughness Effect

When the ocean surface is roughened by wind, the roughness of the surface increases the emissivity. In the modeling of microwave ocean emissivity, the roughness can be modeled on two scales. One is small-scale roughness, i.e., capillary waves whose wavelengths are small compared with the microwave radiation wavelength. The small-scale waves can be considered modulations of large-scale waves. The other is large-scale roughness, i.e., gravity waves or swells whose wavelengths are large compared with the microwave radiation wavelength. The reflectivity under foam-free conditions is defined as follows:

$$|R_{p,\text{Foam-free}}|^2 = |R_{p,\text{Fresnel}}|^2 \times f_s(\nu, \theta, W_s) + f_l(\nu, \theta, W_s), \quad (p = h \text{ or } v) \quad (2.31)$$

where $f_s(\nu, \theta, W_s)$ is the small scale roughness correction factor and $f_l(\nu, \theta, W_s)$ is the large scale roughness correction factor. W_s is 10-m wind speed. Furthermore, the breaking waves produce foam and whitecaps. They increase the emissivity because the foam and whitecaps behave like black bodies in the microwave frequency range.

These three contributions: (i) small scale roughness, (ii) large scale roughness, and (iii) foam and whitecaps are parameterized and have been updated in the development of FASTEM.

In addition, a correction function for azimuthal variation of the emissivity caused by ocean roughness is included in FASTEM.

Small-Scale Roughness Effect

The roughness effect from small-scale waves is a source of Bragg scattering and diffraction in the microwave frequency range. The small-scale roughness effect increases microwave emission. FASTEM-1 adds an empirically derived correction factor (an exponential function of incidence angle) to the Fresnel reflectivity.

In FASTEM-1, the small-scale correction term is included in the diffraction term:

$$|R_p|^2 = |R_{p,\text{Fresnel}}|^2 \exp\left(-\frac{\alpha W_s \cos^2 \theta}{v^2}\right), \quad (p = h \text{ or } v), \quad (2.32)$$

where α is a constant and W_s is the 10-m wind speed. The small-scale correction term is not applied below 15 GHz in FASTEM-1.

Although Bragg scattering by small-scale waves is the dominant effect in the directional signals (Yueh, 1997), there is no azimuthal-dependent model function on the small-scale roughness effect in FASTEM because the surface spectrum is assumed to be isotropic.

Large-Scale Roughness Effect

This phenomenon can be modeled as an ensemble of tilted facets, with each facet being treated as an independent specular surface. In FASTEM, this contribution is integrated and parameterized as a function of incident angle, wind speed, and frequency to achieve fast computational performance. FASTEM-1 parameterized the large-scale roughness effect based on a geometric optics (GO) model output. FASTEM-2 added a correction term to the reflectivity by using surface-to-space transmittance and updated the parameterization coefficients based on the GO model. The emissions from the large-scale wave are assumed to be isotropic in the azimuthal direction.

The large-scale correction terms are then defined as quadratic functions of the 10-m wind speed and the frequency. However, the Fresnel law for calm seas was not maintained for the coefficients in FASTEM-1. FASTEM-4 introduced an improvement to the roughness parameterization based on a two-scale emissivity model.

Foam and Whitecap Effect

Foam emissivity and foam fraction on the ocean surface are important factors under strong wind conditions. Foam emissivity and coverage both increase the emissivity and the brightness temperature measured by satellite microwave instruments. To incorporate the effects of foam on the emissivity under strong wind conditions, accurate foam emissivity and foam fraction models are both needed.

FASTEM-1, -2, and -3 use a constant value (1.0) for the foam emissivity for both polarizations over all incidence angles. The constant value (1.0) of foam emissivity for the horizontal polarization is considered large for a range of incidence angles and may be the cause of the bias in horizontal polarization in FASTEM-1 as seen in Chapter 4.

The reflectivity of the foam is calculated from the foam emissivity as follows:

$$|R_{p,\text{Foam-covered}}(\nu, \theta)|^2 = 1 - \epsilon_{p,\text{Foam}}(\nu, \theta), \quad (p = h \text{ or } v). \quad (2.33)$$

The foam fraction also varies depending on the wind speed. The functions are parameterized based on 10-m wind speed. FASTEM-1, -2, and -3 use the Monahan and O’Muircheartaigh (1986) function

$$f = 1.95 \times 10^{-5} u^{2.55} \exp(0.0861 \Delta T), \quad (2.34)$$

where f is the foam fraction, u is the 10-m wind speed in meters per second, and ΔT is the low-elevation atmospheric stability used in Monahan and O’Muircheartaigh (1986). Here ΔT

is set to zero in FASTEM. Although FASTEM-4 introduced the Tang (1974) foam cover parameterization, the model was changed from Tang (1974) to Monahan and O’Muircheartaigh (1986) in FASTEM-5.

The total reflectivity of the ocean surface $\Gamma(\nu, \theta)$ can be calculated from the foam fraction f and reflectivity of the foam-free and foam-covered parts by using

$$\Gamma_p(\nu, \theta) = f |R_{p,\text{Foam-covered}}(\nu, \theta)|^2 + (1 - f) |R_{p,\text{Foam-free}}(\nu, \theta)|^2, \quad (p = h \text{ or } v). \quad (2.35)$$

2.3.3. Azimuthal Variation

Additionally, the ocean surface radiance observed with microwave radiometers has a wind direction signal (azimuthal variation). In airborne radiometer field experiments during the 1990s, an azimuthal variation was clearly observed (Etkin et al., 1991; Dzura et al., 1992; Yueh et al., 1995, 1997, 1999). The signals vary as a function of the azimuth angle, wind speed, and incidence angle. The models in theoretical studies of ocean surface emissivity (Tsang, 1991; Yueh et al., 1994; Yueh, 1997) were able to explain the azimuthal variation in horizontally and vertically polarized radiance, and in the third and fourth Stokes parameters. Moreover, the signal was found in analyses of space-borne radiometer measurements from the Special Sensor Microwave/Imager (SSM/I: Wentz, 1992; Meissner and Wentz, 2002). These experiments and analyses showed that radiances at 19 and 37 GHz have dependencies on wind direction relative to the sensor viewing angle. In other words, the directional features of ocean surfaces can be measured as the azimuthal variation of the radiances. In geophysical parameter retrievals (e.g., sea-surface temperature, sea-surface wind speed, and total column water vapor) from satellite radiance data, the directional signal had been thought of as an error source and was removed to obtain accurate geophysical parameters. Moreover, the signals are actively used as a geophysical model function (GMF) in wind vector retrievals from scatterometers (QuikSCAT, ASCAT) and WindSat measurements.

Wentz (1997) showed that inclusion of the azimuthal variation in a wind speed retrieval algorithm could significantly improve the accuracy of the wind speed product. Meissner and Wentz (2002) proposed an ocean emissivity model for the oceanic geophysical parameter retrievals, and recently updated their model (Meissner and Wentz, 2012). Their latest model has an updated function to express the azimuthal variation in terms of relative wind direction (RWD), the wind direction relative to the satellite azimuth angle. Their model function was developed based on a collocated dataset of radiance measurements from WindSat and SSM/I, and wind observations from QuikSCAT.

In addition to the three corrections to the ocean surface roughness effects in the reflectivity, a correction model to allow for the azimuthal variation of the emissivity was introduced for the first time in FASTEM-3. The model was developed from measurements by the WindRad radiometer operated by the Jet Propulsion Laboratory and a model proposed by St. Germain et al. (2002) that based on aircraft measurements. FASTEM-3 uses a model function of the azimuth line-of-sight minus the wind direction. FASTEM-4 and FASTEM-5 updated the azimuthal function based on a theoretical two-scale model output, so they are no longer based

on real microwave measurements from satellites. The FASTEM-4 and FASTEM-5 azimuth model functions use the RWD as the input to express the azimuthal variation instead of the azimuth line-of-sight minus the wind direction. FASTEM-3 and FASTEM-5 use harmonic cosine functions to express the variation. The Meissner and Wentz (2012) model function uses similar harmonic cosine functions for the modeling.

2.3.4. Update History of FASTEM in RTTOV

The initial version of FASTEM (FASTEM-1) was based on GO model simulation results. FASTEM-2, by Deblonde and English (2001), was released in RTTOV-7 (Saunders et al., 2002). An azimuthal variation model function was introduced for the first time in FASTEM-3 (Liu and Weng, 2003), released as part of RTTOV-8 (Saunders et al., 2006). In FASTEM-4 (Liu et al., 2011), an updated permittivity calculation, new parameterization of the roughness effect, foam parameterization, and a new azimuthal model function were introduced. FASTEM-5 again modified the large-scale roughness and foam parameterizations. FASTEM-4 and -5 are incorporated in RTTOV-10 (Saunders et al., 2012) and RTTOV-11 (Saunders et al., 2013). The impact of FASTEM-4 and FASTEM-5 on NWP was evaluated at the European Centre for Medium-range Weather Forecasts (ECMWF) and FASTEM-5 was selected for operational use (Bormann et al., 2011, 2012).

3. Satellite Radiance Assimilation in the JMA Operational Mesoscale 4DVAR System

3.1. Introduction

Theoretically, direct radiance assimilation is superior to retrieval assimilation because complicated error contamination in various retrieval processes can be avoided. Furthermore, the radiance assimilation allows for the early introduction of the radiance data into the operational systems. Moreover, its rapid, real-time processing without the retrieval steps is an advantage for operational data usage.

In practice, biases between the observed and simulated radiances are present and should be properly corrected. Eyre (1992) proposed a bias correction method that can estimate the bias from two components. The first component is dependent on the scan angle; the second component depends on the air mass. Moreover, the airmass-dependent bias is expressed as a linear function of several predictors. The coefficients of the predictors are assumed to be channel dependent and can be determined offline (Harris and Kelly, 2001) or adaptively updated within a minimization process in the variational assimilation system (VarBC; Dee, 2005).

Although the VarBC method is widely used in global data assimilation systems, a bias correction method for regional data assimilation has not been established because of difficulties in estimating the biases within limited regions and times. The global radiance dataset contains observational information on various meteorological conditions. However, meteorological phenomena in a regional model are not sufficient to capture general trends in the radiance bias within its limited domain. Polar-orbiting satellite coverage is nonuniform in the limited area and highly variable. Therefore, adaptively estimated bias coefficients using only the regional model information and limited sampled radiance data are not as robust as those used in the global systems. Moreover, the model-top height generally restricts the usage of high peaking channels. Regional models often focus on weather events in the troposphere, and the model-top height is set lower than in global models to save computational costs in the operational system. This limitation might cause additional bias in the simulated radiances. Handling the radiance bias correction in the regional data assimilation is challenging, and the best solution remains an open topic.

Accurate precipitation forecasting is one of the most important tools in preventing natural disasters. The Japan Meteorological Agency (JMA) operates a global NWP system and a

mesoscale NWP system to provide guidance for issuing warnings and very short-range forecasts of precipitation in Japan and its surrounding areas (JMA, 2013). Japan is an island country and suffers annually from the heavy precipitation caused by typhoons and seasonal fronts. The main source of the precipitation is moisture coming from the ocean. Therefore, the use of satellite observation data gathered from over the oceans is critical in the analysis of the JMA mesoscale NWP system to produce correct and accurate initial conditions.

A dense, ground-based observation network is available in and around Japan, including surface weather stations, ground-based radars, upper-air soundings from radiosondes and aircraft, wind profilers, drifting buoys, ships, and ground-based GPS-integrated water vapor data over the land. These *in situ* observations and ground-based remote sensing data can capture the fine structure and rapid changes of mesoscale phenomena over short time intervals in some areas. However, the available ground-based data collection areas are limited to land-based systems and locations near the coast. Therefore, there are many temporal and spatial gaps in the data coverage.

In contrast, remote sensing observation platforms in space provide wide coverage of temperature, moisture, and wind. Geostationary satellite data are available at high-frequency time intervals. With regard to polar-orbiting satellites, although the temporal frequencies are not sufficient for use in operational regional models, data from multiple satellites can be used to fill gaps. Frequent analysis updates enable the representation of the fine structures and rapid changes of mesoscale phenomena in the initial NWP fields.

In the JMA mesoscale NWP system [sections 3.7 and 4.5 of JMA (2007)], satellite data have been retrieved from several sources, including temperature profiles from the operational polar-orbiting meteorological satellites' temperature sounders [the National Oceanic and Atmospheric Administration (NOAA) and Meteorological Operational Satellite (MetOp) Advanced TIROS Operational Vertical Sounders (ATOVSs)] and the total precipitable water and rain rate from research and development satellite microwave imagers [the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I), the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), and the Aqua Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E)]. The information on temperature and moisture from the satellite data has been indispensable in the production of realistic initial fields and forecasts. The observational data used in the JMA mesoscale NWP system are outlined in section 3.2 of JMA (2007) and section 2.2 of JMA (2013).

The primary goal of this study is to examine the impact of satellite radiance assimilation in the JMA operational mesoscale NWP system. In the development of the radiance assimilation scheme for the mesoscale system, the same radiative transfer model (RTTOV-9) and the same preprocessor (Okamoto et al., 2005) were applied. However, as discussed above, a bias correction scheme in the regional model has not been established, and it is necessary to develop a method to handle the lower model-top height in the mesoscale model. To overcome these difficulties for the mesoscale system, two modifications were applied to the preprocessor. First, the data-thinning distance was shortened. The second modification was to extrapolate the atmospheric profile from the mesoscale model top to the radiative transfer model top using the *U.S. Standard Atmosphere, 1976* lapse rates. Moreover, estimated bias correction coefficients in

the global radiance assimilation system were adopted for use in the mesoscale system. Before the radiance assimilation scheme was operational, experiments comparing radiance assimilation and retrieval assimilation were conducted using the JMA mesoscale NWP system. These experiments demonstrated the advantage of radiance assimilation in the operational mesoscale data assimilation system. Several data-denial experiments were performed to a typhoon event to investigate the effects of individual radiance components on the mesoscale forecasts. The denial experiments revealed the impacts of the radiance dataset in the mesoscale analysis and demonstrated the positive effects of the radiance data assimilation in the typhoon case.

Section 3.2 describes the JMA mesoscale analysis system, its preprocessor, and the modifications of the mesoscale system. Section 3.3 introduces the experiments that compare the radiance data assimilation and the retrieval data assimilation using the operational configuration. Section 3.4 explains the denial experiments for the typhoon case. Finally, discussion is provided in section 3.5.

3.2. The Mesoscale Analysis System

3.2.1. Forecast Model and Analysis System

JMA introduced the world's first regional four-dimensional variational data assimilation (4DVAR) system in 2002 (Ishikawa and Koizumi, 2002), and the JMA mesoscale model was upgraded to a non-hydrostatic model (Saito et al., 2006) in 2004. A non-hydrostatic model-based 4DVAR system, the JMA Non-hydrostatic Model-Based Variational Analysis Data Assimilation scheme (JNoVA; Honda et al., 2005), replaced the former hydrostatic 4DVAR scheme in 2009 (Honda and Sawada, 2009). The initial fields for the forecasts are produced in JNoVA. The analyses are performed every 3 h. The JMA mesoscale model produces short-range forecasts (15-h forecasts from 0000, 0600, 1200, and 1800 UTC initializations and 33-h forecasts from 0300, 0900, 1500, and 2100 UTC initializations). The model domain covers Japan and its surrounding areas (Figure 3.1).

Each analysis involves a 3-h assimilation time window. The cutoff time for receiving data is 50 min after the end of the assimilation window. For the mesoscale analysis, a high-resolution (5-km horizontal resolution) forecast model is used for the assimilation window to obtain the first-guess field and departures from the observations, and the first guess is calculated. This process is called the first outer loop, and the model is called the outer model. Then, a minimization process to find an optimal field is executed on a low-resolution (15-km horizontal resolution) domain. This process is called the inner loop, and the low-resolution model is called the inner model. For the minimization of a cost function in the low-resolution space, a simplified nonlinear version of the mesoscale model is used to provide trajectories at every iteration instead of a tangent linear model of the mesoscale model because of discontinuity and non-linearity. An adjoint model of the mesoscale model provides gradient information. The JMA analysis system uses an incremental approach (Courtier et al., 1994). Estimated analysis increments in the low-resolution space are added to the high-resolution first guess. Moreover,

CHAPTER 3. SATELLITE RADIANCE ASSIMILATION IN THE JMA OPERATIONAL MESOSCALE 4DVAR SYSTEM

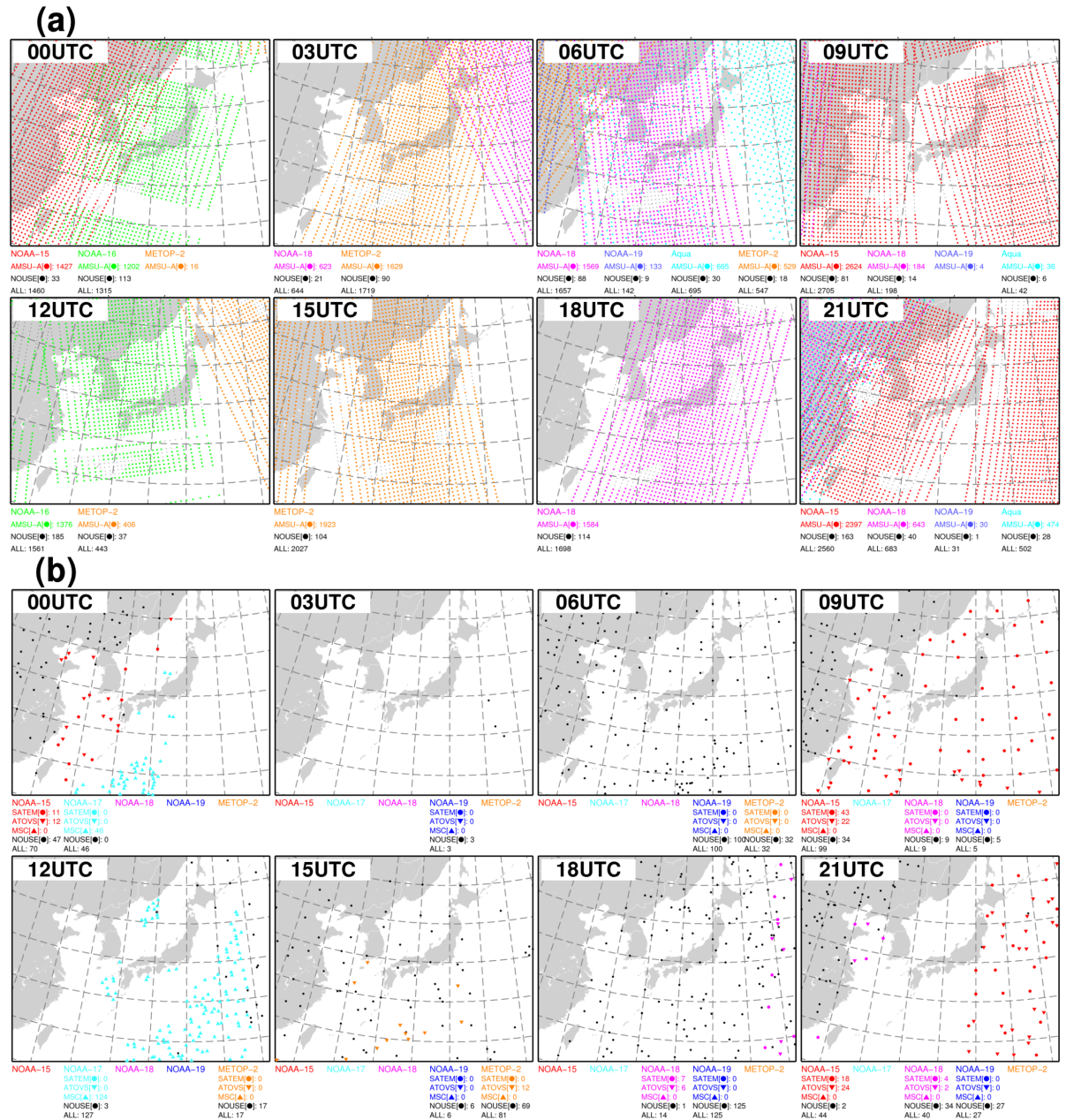


Figure 3.1. Data coverage of (a) AMSU-A radiance data and (b) ATOVS temperature retrievals over 3-h analysis times in the JMA mesoscale model domain on 1 Jul 2010. In (a) and (b), non-black-colored points indicate the data ingested into the analysis after the quality control. Small black-colored points indicate rejected data in the quality control.

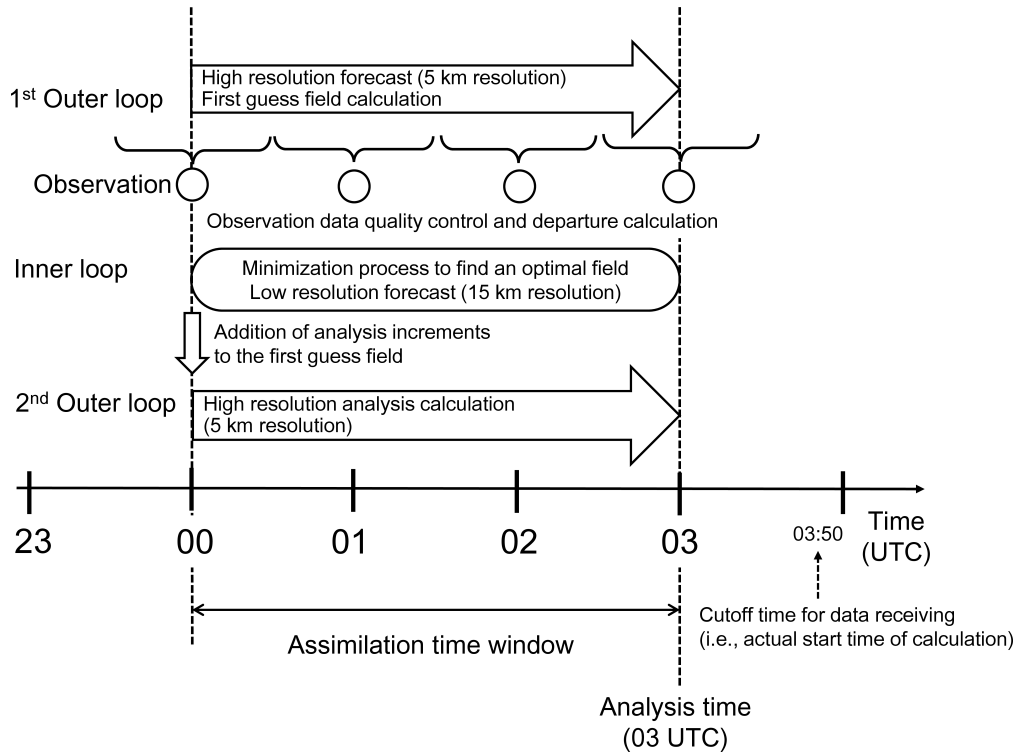


Figure 3.2. Schematic procedure of mesoscale analysis for 03 UTC analysis case.

the high-resolution (5-km horizontal resolution) forecast model is used for the data assimilation window to obtain the initial conditions. This final step is called the second outer loop, and the high-resolution model in the outer loops is called the outer model. The outer model is the same model used for the mesoscale forecast product (33-h forecast). Two outer loops and one inner loop are used for the JMA mesoscale 4DVAR system. The outer model has 50 vertical levels and the inner model for the minimization in the data assimilation has 40 vertical levels. The model-top height for both models is approximately 22 km (approximately 40 hPa). The lateral boundary conditions for the analyses are obtained from the JMA global model forecast. The initial field as the first guess is taken from the previous mesoscale analysis. A schematic procedure of the mesoscale analysis for 03 UTC analysis case is shown in Figure 3.2 A full description of the JMA NWP system is summarized in JMA (2013).

3.2.2. Observational Data in the JMA Mesoscale NWP System

In the JMA operational mesoscale NWP system, various real-time observational data are available. In terms of conventional data, reports from surface weather stations, ships, and buoys (surface pressure); ground-based radar data (wind and retrieved relative humidity); upper-air sounding data with radiosondes (temperature, humidity, and wind); aircraft data (temperature and wind); wind profilers (wind); and ground-based GPS integrated water vapor data

are available. For typhoons over the western North Pacific, bogus typhoon data, as a form of pseudo-observations are generated with a statistical method and assimilated for a realistic tropical cyclone structure analysis. The data are surface pressure and wind profiles from 1000 to 300 hPa (JMA, 2013). Additionally, atmospheric motion vectors (wind data) from a geostationary satellite (Multifunctional Transport Satellite, MTSAT) derived by tracking successive cloud and moisture features are available. In terms of radiance data, polar-orbiting satellite [i.e., Aqua AMSR-E, TRMM TMI, DMSP SSM/I (and Special Sensor Microwave Imager/Sounder, SSMIS), NOAA Advanced Microwave Sounding Unit A (AMSU-A) and Microwave Humidity Sounder (MHS), and MetOp AMSU-A and MHS radiances] and geostationary satellite [i.e., MTSAT Clear Sky Radiance, (CSR) data are available. CSR data from MTSAT-1R and -2 are routinely produced in the JMA Meteorological Satellite Center (MSC; Uesawa, 2009, 39 - 48). The MTSAT CSR data are hourly clear-sky radiance data and are produced in real time. The data are superobbing data of MTSAT clear-sky radiance data. The horizontal grid size of the superobbing is 60 km. The data include quality information, for example, the mean, maximum, and minimum values, as well as the standard deviation, for the sampled clear-sky radiances in the superobbing. Moreover, the data cover the hemisphere centered at 140° east, including Japan and Australia. Because MTSAT-1R was in operational mode during the experiment periods in this study, MTSAT-1R CSR data were used instead of the MTSAT-2 CSR data.

In addition to the global data delivered from the National Environmental Satellite, Data, and Information Service (NESDIS) through the Global Telecommunication System (GTS) and the Internet, NOAA and MetOp satellite data are directly received at the JMA MSC. Moreover, data exchanged through the World Meteorological Organization (WMO) Regional ATOVS Retransmission Service (RARS; WMO, 2009) in the Asia-Pacific region are also available in real time. The typical coverage of operationally available AMSU-A radiance and temperature data in the mesoscale model domain is shown in Figure 3.1. The mesoscale analysis uses the same domain as the mesoscale model. Because the radiance data are level 1 data, all observed data are reported and can be applied using quality controls (QCs) developed in this study. In contrast, the retrieved products are reported only as clear-sky data. The QCs that are applied to the products depend on the data providers (NESDIS and MSC). Therefore, the data volume of the retrievals is small, and there are many space and time gaps in the coverage.

3.2.3. Preprocessor for the Radiance Data in the Mesoscale Data Assimilation System

Preprocessing of radiance assimilation is one of the most important processes in the data assimilation system. Data selection (e.g., data thinning and bad data rejection) is performed in this process. The radiance data under the clear-sky conditions are assimilated in the current JMA global NWP system (JMA, 2013; Okamoto et al., 2005). Cloud screening is based on the retrieved cloud liquid content data (Okamoto et al., 2005; Kazumori, 2009b). RTTOV-9 (Saunders, 2008) is implemented in the JMA global data assimilation system (Kazumori,

2009a) as an observation operator to calculate the radiance and the Jacobian in the variational data assimilation. The same radiative transfer model (RTTOV-9) is introduced into the preprocessor and the analysis system itself as the radiative transfer model for the radiance calculation in the mesoscale analysis. In the preprocessing step, innovation vectors (e.g., observed brightness temperature minus simulated brightness temperature, O - B departure) are calculated using atmospheric fields and surface properties (surface temperature and wind) from the most recently produced mesoscale forecast fields using the high-resolution outer model in the mesoscale NWP system.

Because the same radiative transfer model that is used in the JMA global system was selected for the preprocessor and for the 4DVAR analysis in the mesoscale system, QCs based on the models used for the radiance data in the JMA global analysis (JMA, 2007; Okamoto et al., 2005) can be applied. However, two modifications were made to the QCs for radiance assimilation in the mesoscale system.

The first change is in the treatment of the atmospheric profiles for the radiative transfer calculation. The model-top height is different between the global model and the mesoscale model. The global model-top height is approximately 0.1 hPa, and the atmospheric profiles from the global model have 60 vertical levels to cover the atmosphere from the surface to the stratopause, whereas the mesoscale model-top height is approximately 40 hPa. The mesoscale model-top height is not sufficiently high to incorporate the higher peaking channels of the temperature-sounding instruments (AMSU-A) in the radiance calculations. Therefore, the atmospheric profiles from the mesoscale model are extrapolated from the mesoscale model-top height using the *U.S. Standard Atmosphere, 1976* lapse rates to fill gaps in the upper-air levels. Figure 3.3 depicts the relationship of the model-top height and the weighting function of the assimilating radiance data in the mesoscale analysis. The weighting functions indicate sensitive range of the each channel vertically. Figure 3.4(a) compares the O - B departure with and without profile extrapolation for all AMSU-A channels. Figure 3.4(b) compares the O - B departure calculated from the global model with the mesoscale model fields. The extrapolation of the input profiles substantially reduced errors in the calculated brightness temperature, and the remaining biases of O - B departure became approximately zero. It is clear that the profile extrapolation and the bias correction are necessary for the use of sounding channels from the AMSU-A in the data assimilation. However, for certain higher-peaking channels (i.e., AMSU-A channel 9 and above), degradation in the accuracy of the calculated radiance remains. The remaining degradation is caused by a lack of information in the upper troposphere and stratosphere from the input profile used in the radiative transfer calculations. These higher-peaking channels were blacklisted in the mesoscale data assimilation system. However, these channels are used in the JMA global system.

The other modification is made with respect to the data-thinning distance. To reduce the horizontal correlation of the observational errors and reduce the computation time in the radiance calculation for the analysis, data thinning is widely used in satellite radiance assimilation. Because the horizontal resolution between the global (approximately 20 km) and the mesoscale models (5 km) differs, the meteorological phenomena represented in the numerical model are also thought to be different. The horizontal data-thinning distance in the mesoscale system was

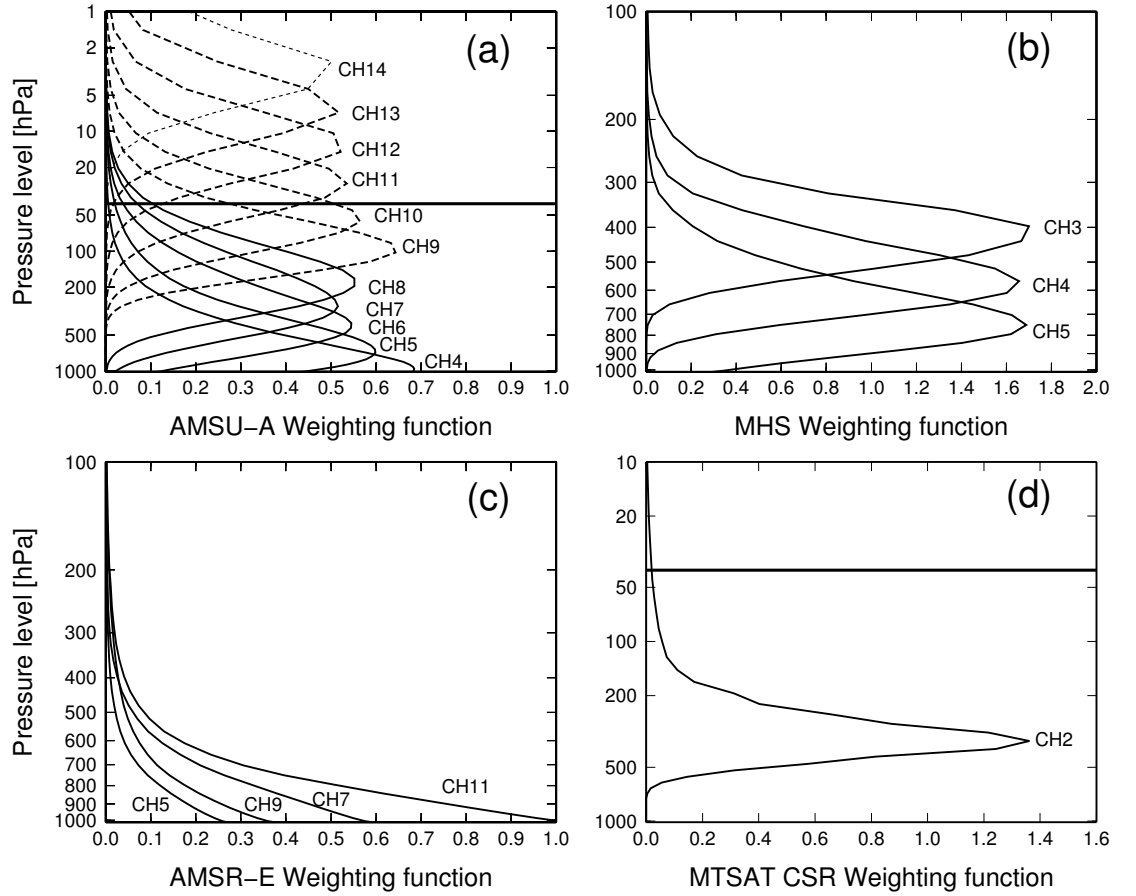


Figure 3.3. Weighting functions of (a) AMSU-A, (b) MHS, (c) AMSR-E, and (d) MTSAT. Only assimilated channels in the JMA NWP system are shown, except for AMSU-A channel 14. Solid curves indicate weighting functions used in both the global data assimilation system and the mesoscale data assimilation system. Broken lines in (a) indicate weighting functions used only in the global data assimilation system. The straight lines in (a) and (d) indicate the mesoscale model-top height.

3.2. THE MESOSCALE ANALYSIS SYSTEM

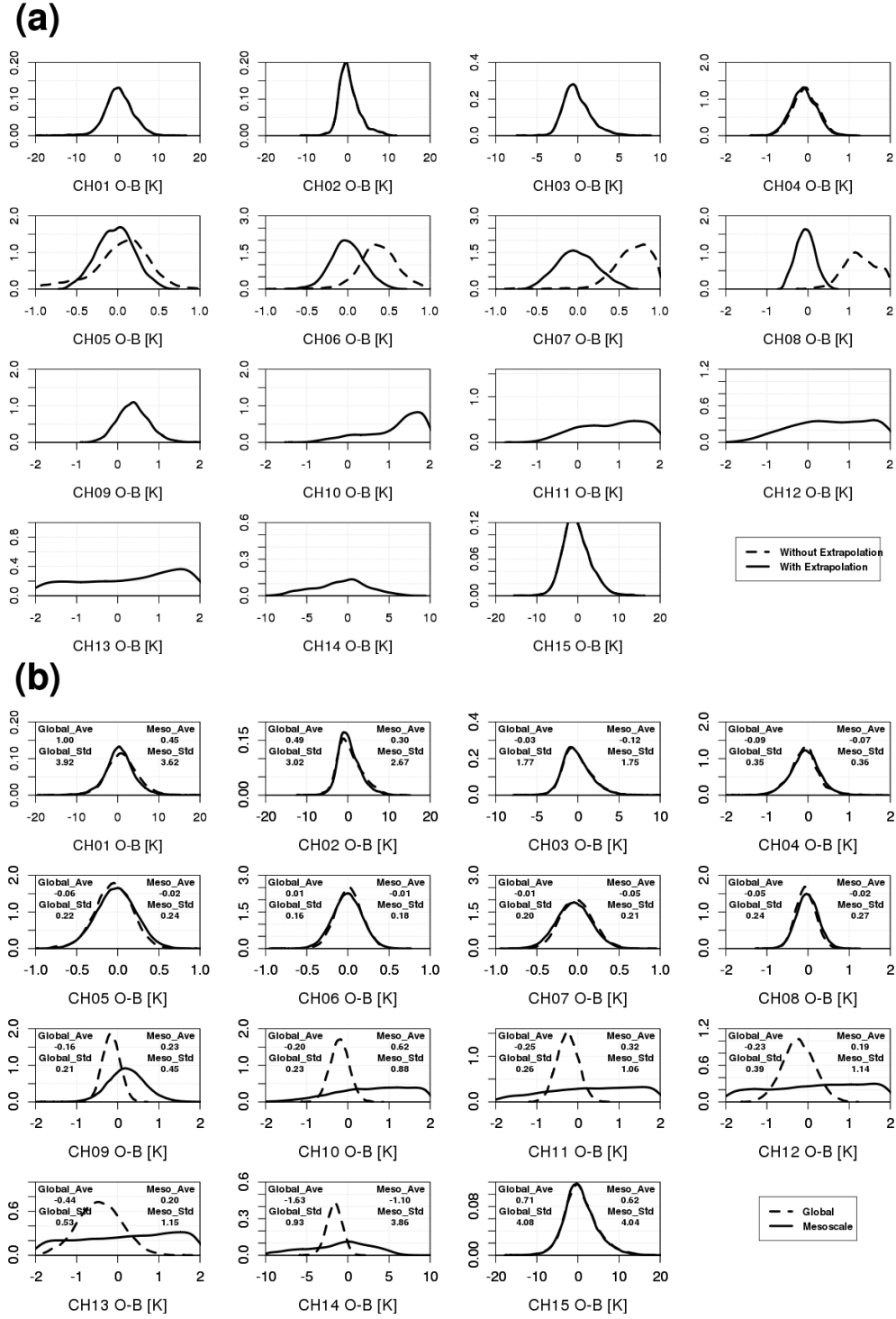


Figure 3.4. (a) Comparison of the AMSU-A brightness temperature O - B departure histogram between the profile with extrapolation (solid line) and without extrapolation (dashed line) for 18 Sep 2009. (b) Comparison of the AMSU-A brightness temperature O - B departure histogram between the mesoscale model with profile extrapolation (solid line) and the JMA global model (dashed line) for Oct 2011. The histograms indicate the frequency distribution of NOAA-18 AMSU-A O - B departure after QC and bias correction.

set to 45 km to reflect its higher resolution (5 km for the outer model and 15 km for the inner model). The data-thinning distance for the global data assimilation system was set to 160 – 250 km, depending on the sensor type. Because the horizontal resolution of the microwave radiometers varies between sensors and MTSAT CSR data have approximately 60 km horizontal resolution, the data-thinning distances were empirically determined. MTSAT CSR data were not thinned. Using denser data with short distance thinning requires substantial computational time in the preprocessor and the analysis. Moreover, the observational information might be assimilated redundantly because adjacent fields of view from the microwave sensors overlap in some areas. In addition, identical observation errors were assigned with the global analysis (Okamoto et al., 2005) for the mesoscale analysis. The data assimilation system may not use an optimal observation error setting. Empirically the data-thinning distance was reduced to 45 km. The reduced thinning distance did not show any negative effects. However, one of the important roles of the data thinning is to avoid difficulty in explicitly treating observation error correlations for time and space in a data assimilation system. Future investigations regarding the data-thinning distance and the correlated observation errors when using high-frequency and high-density radiance data (e.g., next generation’s geostationary satellites) are necessary.

3.2.4. Cloud Screening

Although the retrieved rain rate from microwave imagers (Takeuchi and Kurino, 1997; Sato et al., 2004) is assimilated with the rain rate derived from the ground-based radar data (Koizumi et al., 2005) for rainy areas, the radiance data from AMSU-A, MHS, and MTSAT are assimilated only under clear-sky conditions.

Therefore, it is necessary to employ cloud screening to avoid the contamination of cloud- and rain-affected radiance data in the assimilation system. Methods identical to those used in the global system were adopted for the mesoscale system. Cloud liquid water is derived from observed radiance data. A retrieval algorithm (Kazumori et al., 2012) was applied to microwave images to obtain cloud liquid water. For AMSU-A instruments, the NESDIS cloud liquid water algorithm (Weng et al., 2002) was utilized. Based on the amount of cloud liquid water, cloud screenings were performed. The threshold of the cloud liquid water was set at 200 g m^{-2} . Kazumori et al. (2008) (see Table 5) used a threshold of 100 g m^{-2} for the 37-GHz channel of the microwave imager (AMSR-E) for cloud screening. Although this stringent threshold can select purely clear conditions from the data, the threshold was slightly relaxed from 100 to 200 g m^{-2} to include thin cloudy data. The change in the threshold was acceptable because the retrieved cloud liquid water is used as one of the predictors in VarBC. The clear-sky microwave radiances are assimilated in the mesoscale data assimilation system; the remaining cloud contamination effect is adjusted in the bias correction. For the MHS, a scattering index of 89/150 GHz (Bennartz et al., 2002) and a gross error check of the O - B departure of the window channels are used to remove the cloud and scattering effects caused by hydrometeors in the atmosphere. The CSR data from the MTSAT-1R and -2 produced in the JMA MSC are assimilated into the mesoscale system. The validity of the cloud detection algorithm was confirmed using O - B departure statistics. The distribution of

the O - B departures is expected to follow a Gaussian distribution when cloud-affected data are rejected and biases are properly corrected. The Gaussian distribution for the O - B departures after QC and bias correction was confirmed.

It should be noted that, as discussed in the previous section, AMSU-A channels 4 – 8 are selected for the assimilation. However, the surface-sensitive data are removed because the accuracy of the simulated radiances is inadequate for assimilation because of the insufficient accuracy of the input surface temperature and land emissivity for the radiative transfer calculation. The effects of AMSU-A channels 1 – 3 and 15 in the JMA global analysis system have not been fully investigated nor assimilated. Therefore, updates to the bias coefficients in the operational system are not available for those channels. These channel selection criteria are identical to those of the global analysis (Okamoto et al., 2005). With respect to microwave imagers (AMSR-E, SSMIS, and TMI), only vertically polarized channels (19, 23, 37, and 89 GHz) over the ocean were assimilated to obtain column water vapor information. To avoid the uncertainty of land surface emissivity in the radiative transfer calculation, an infrared moisture channel (6.7 μm) from MTSAT CSR was selected for assimilation because the channel is less sensitive to the surface. For MHS channels 3 – 5, a water vapor absorption line at approximately 183 GHz was also assimilated over the ocean. The weighting functions of the channels used in the mesoscale system are shown in Figure 3.3.

3.2.5. Bias Correction

Radiance biases should be properly corrected before data assimilation because the variational data assimilation method assumes no bias in either the observations or the forecast models. A variational bias correction scheme is commonly used in the global data assimilation system (Dee, 2005). In the JMA global analysis, VarBC schemes are used to correct radiance data bias (Sato, 2006a). The biases are estimated with a linear function using several predictors; the coefficients are updated to capture seasonal and daily changes in the biases. However, because of nonuniform coverage of the radiance data in the limited areas of the model, the estimation of the radiance bias inside the mesoscale system is more difficult to ascertain than in the global system. The coverage and available data depend on the satellite orbits, and the data delivery conditions of the GTS and the Internet vary in every analysis. Therefore, the estimated radiance biases in the mesoscale analysis may be highly situation dependent, based on the meteorological conditions and/or polar-orbiting satellite data coverage. This variability may cause an over-fitting in the bias correction, which may cause the estimated bias correction coefficients to be unstable in a time series. Therefore, bias correction coefficients determined from the latest global analysis in the JMA NWP system are used. The coefficients produced with the global data are much more stable and robust. The coefficients are updated every 6-h in the global data assimilation cycle. The latest updated coefficients estimated in the global analysis are utilized for the mesoscale system, and the same set of predictors in the global analysis is also used in the mesoscale system. With respect to the AMSU-A, the integrated lapse rate, surface temperature, cloud liquid water, and satellite zenith angle are used. The MHS uses the same predictors as the AMSU-A except that it does not use cloud liquid water.

With respect to microwave imagers, total precipitable water, surface temperature, surface wind speed, and cloud liquid water are used. Finally, the simulated brightness temperature and sensor zenith angle are used for the MTSAT CSR.

The same bias correction coefficients can be used because it is implicitly assumed that the difference between the radiance biases in the global model and the mesoscale model in terms of the O - B departures are not large, and the same radiative transfer model RTTOV-9 is used in the JMA global and mesoscale data assimilations. The bias-corrected O - B departures shown in Figure 3.4(b) suggest that the use of the coefficients estimated in the global system for the selected channels is acceptable for the mesoscale system.

3.3. Experiments with the JMA Mesoscale 4DVAR System

3.3.1. Experimental Configuration

Before the operational implementation of the radiance assimilation scheme, two assimilation experiments were configured to examine the effects of radiance assimilation in the mesoscale system. The first run (Control run) was set up identically to the operational configuration of the JMA mesoscale NWP system as of October 2010. The Control run did not directly use any radiance data. The Control run assimilated conventional observations, including surface pressure data from meteorological observation stations and ships; temperature, wind, and relative humidity data from radiosondes; and aircraft; wind and rain-rate data from ground-based radars; satellite wind data (MTSAT atmospheric motion vector); and retrieved data [e.g., temperature profiles from ATOVS and total precipitable water vapor (TPW) and rain rate from microwave imagers]. The second run (Test run) assimilated radiances from ATOVS (AMSU-A, MHS), AMSR-E, TMI, and SSM/I(SSMIS) on board polar-orbiting satellites and geostationary satellites (MTSAT CSR), in addition to the conventional observational data used in the Control run. However, the retrievals (temperature profiles and TPW) were removed in the Test run to avoid information from the same data source being used twice. Rain-rate retrievals from microwave imagers were used in both the Control and Test runs. DMSP F-16 and F-17 SSMIS microwave imager radiances and rain rates were newly added in the Test run. The data used in both runs were delivered within the operational data receiving cutoff time.

Three-hourly assimilation cycles were performed for three selected periods and ran the mesoscale model to produce 33-h forecasts from 0300, 0900, 1500, and 2100 UTC initialization fields every day. The three periods were selected to examine the performance of the radiance assimilation on typical meteorological phenomena and hazardous weather events caused by heavy precipitation in Japan. The periods from 16 to 26 July 2009 and from 1 to 5 July 2010 include heavy rainfall events caused by seasonal fronts, and the period from 9 to 12 August 2010 includes a typhoon.

The data coverage of the temperature retrievals and the raw radiances varies for different analysis times, as shown in Figure 3.1. The data from polar-orbiting satellites vary temporally, and in most cases, the data are available for two analysis times per day and cover some

3.3. EXPERIMENTS WITH THE JMA MESOSCALE 4DVAR SYSTEM

fraction of the mesoscale model domain. The large data volume is an advantage of using radiances in the analysis. It should be noted that two runs were not clean comparisons between the radiance assimilation and the retrieval assimilation because the volume of data used was different. However, this type of comparison is important from an operational standpoint. The configurations of the dataset used in both runs are summarized in Table 3.1.

Table 3.1. The physical quantity related to the radiance data for each satellite/sensor that was used in the experiments.

	Satellite/sensor	Control run	Test run
Microwave imager	Aqua/AMSR-E	Total precipitable water, rain rate	Radiance, rain rate
	DMSP F-16/SSMIS	N/A	Radiance, rain rate
	DMSP F-17/SSMIS	N/A	Radiance, rain rate
	TRMM/TMI	Total precipitable water, rain rate	Radiance, rain rate
Microwave temperature sounder	DMSP F-16/SSMIS	N/A	Radiance
	NOAA-15/AMSU-A	Temperature	Radiance
	NOAA-16/AMSU-A	N/A	Radiance
	NOAA-18/AMSU-A	Temperature	Radiance
	NOAA-19/AMSU-A	Temperature	Radiance
	MetOp/AMSU-A	Temperature	Radiance
	Aqua/AMSU-A	N/A	Radiance
Microwave humidity sounder	NOAA-15/AMSU-B	N/A	Radiance
	NOAA-16/AMSU-B	N/A	Radiance
	NOAA-17/AMSU-B	N/A	Radiance
	NOAA-18/MHS	N/A	Radiance
	NOAA-19/MHS	N/A	Radiance
	MetOp/MHS	N/A	Radiance
IR sounder	NOAA-17/HIRS	Temperature	N/A
	Aqua/AIRS	N/A	N/A
	MetOp/IASI	N/A	N/A
IR imager	MTSAT-1R/Imager	N/A	Radiance

N/A = Not available in the experiment.

3.3.2. Results

The accuracy of the analysis and the forecast were considerably improved with the radiance assimilation. Figure 3.5 shows the profiles of the RMSEs of the geopotential height forecast against radiosonde observations. To show the difference in RMSEs between the Control run and the Test run, an improvement ratio is defined as the relative value of the improvements for each pressure level. The ratio is calculated with the following equation:

$$\text{Improvement ratio (\%)} = \frac{\text{RMSE of the Control run} - \text{RMSE of the Test run}}{\text{RMSE of the Control run}} \times 100. \quad (3.1)$$

In Figure 3.5(c), positive values indicate reductions in RMSEs in the Test run. In the Control run (Figure 3.5(a)), the RMSE of the forecast time (FT) = 3 (solid line) was larger than that of FT = 9 (dashed line), whereas the RMSE increases with the forecast time in the Test run (Figure 3.5(b)). The verified forecasts were produced from 0900 and 2100 UTC analyses at

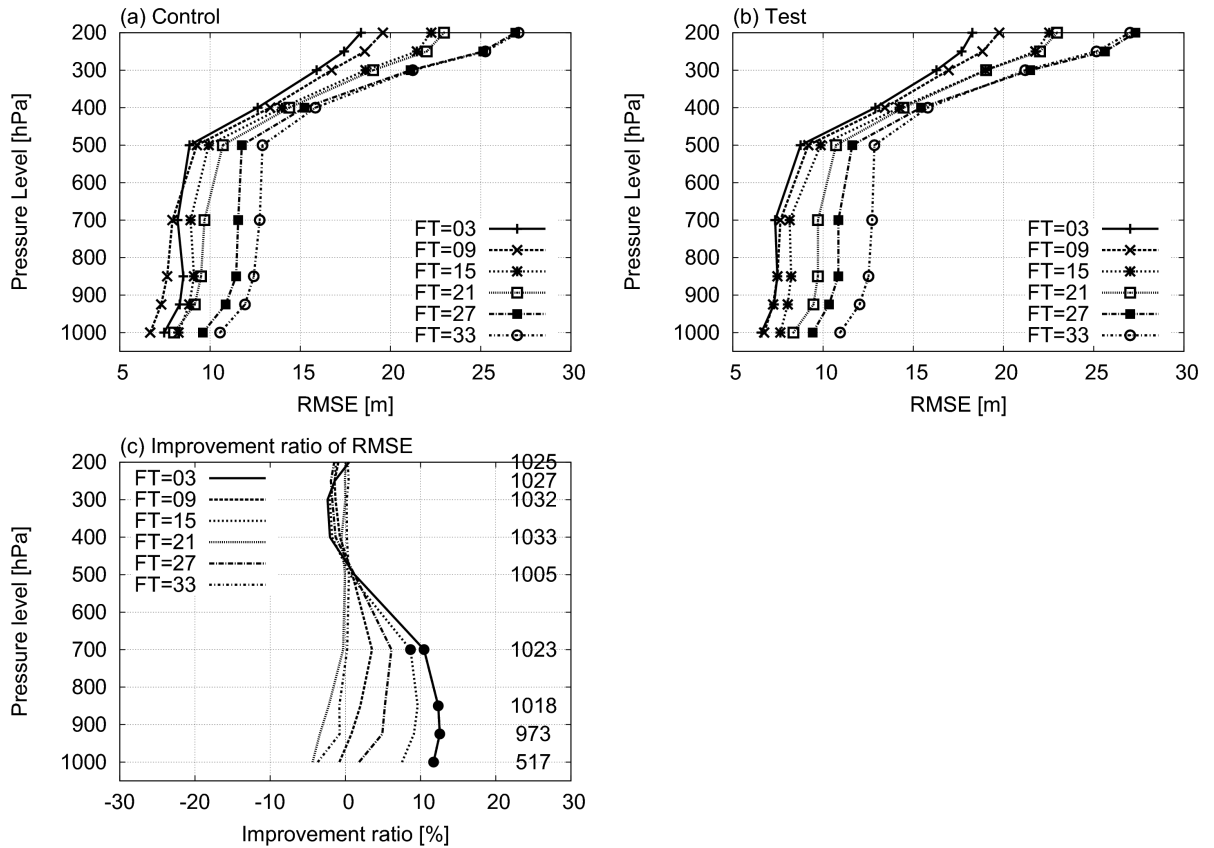


Figure 3.5. RMSE of the geopotential height forecast for the mesoscale model against the radiosonde observations from 16 to 26 Jul 2009. The forecasts from the 0300, 0900, 1500, and 2100 UTC initializations were verified. The verified times were 0000 and 1200 UTC. The line type indicates the difference in forecast time (FT): solid, FT = 3; dashed, FT = 9; dotted, FT = 15; fine dotted, FT = 21; dotted-long dashed, FT = 27; and dotted-short dashed line, FT = 33. Shown are the (a) Control run, (b) the Test run, and (c) the improvement ratio of RMSE (%; see text for the definition). Plotted numbers on the right-hand side in (c) are the observation counts used in the verification. Statistical significances at 90% level using a t test are displayed with filled circles in (c).

FT = 3 and FT = 15 in the forecast verification, respectively. In these analyses, radiosonde data were not available in the assimilation time window. However, radiosonde data were available in the assimilation time windows for other analyses (e.g., 0300 and 1500 UTC). Typically, radiosonde data are generated at 0000 and 1200 UTC. The lateral boundary conditions (JMA global model forecast) produced from 0600 and 1800 UTC initializations are available for the 0900 and 2100 UTC analyses, respectively. Moreover, the global model forecasts from 0000 and 1200 UTC initializations are available for the 0300 and 1500 UTC mesoscale analyses within the JMA operational system's job schedule framework. It is likely that the global forecasts from 0000 and 1200 UTC have better quality in the mesoscale model domain than others because the radiosonde data around Japan are available for these global analysis times. In the Test run, the improvement of the RMSE in the short-range (FT = 3 and FT = 15) forecasts in the lower troposphere from 1000 to 500 hPa was remarkable. The results from the Test run are normal for the growth of NWP model errors. The reason for the existing degradation in the short-range forecast accuracy in the Control run is thought to be related to unbalanced data coverage and the amount of conventional data in the 3-h cycle of the mesoscale analysis. The use of satellite radiance data in place of the retrieval data compensated for the lack of observation information in the assimilation cycle. The effects on the upper troposphere and lower stratosphere were small. One possible explanation for this lessened effect is that higher peaking radiance data were not used in the mesoscale system. Another possible reason is that the upper layers (near 40 hPa) in the mesoscale model are used as relaxation layers for the lateral boundaries, and the analysis increments were suppressed vertically to balance the lateral boundary condition (from the global model) with the mesoscale model.

As for moisture-related observations, TPW retrievals from AMSR-E and TMI were assimilated in the Control run, whereas AMSR-E and TMI radiance data were directly assimilated in the Test run. The microwave imagers are thought to provide similar moisture information because most of the moisture is typically concentrated in the lower part of the atmosphere, and the information from microwave imagers is considered in the total column amount (not the sounding information). DMSP F-16 and F-17 SSMIS-retrieved TPW products were not used in the Control run because the corresponding retrievals were not ready at the time of the experiment. SSMIS, MHS, and MTSAT (infrared water vapor channel) radiance data were newly added in the Test run. These data-sets provide new lower- and upper- tropospheric moisture observation information. In the analysis, these data largely increased the moisture content and strengthened the TPW contrast between moist and dry areas in a typhoon event, as shown in Figure 3.6. In this case, the subtropical high pressure system was located east of Japan (see Figure 3.6(e)). The high pressure system was characterized by 30 – 40 mm in the TPW range (green areas in Figures 3.6(a),(c)), whereas moisture flow along the high pressure boundary was described by 50 – 70 mm in the TPW range. The TPW analysis increment along the coast of Japan was similar in the Test and Control runs. However, over the ocean, the Test run TPW analysis increment was much larger and wider than that of the Control run. Because the ground-based GPS TPW and the rain rate from ground-based radar were used in both the Test and Control runs, the runs produced a similar increment around Japan. The addition of the new F-16 and F-17 SSMIS microwave imagers increased the increment over the ocean.

CHAPTER 3. SATELLITE RADIANCE ASSIMILATION IN THE JMA OPERATIONAL MESOSCALE 4DVAR SYSTEM

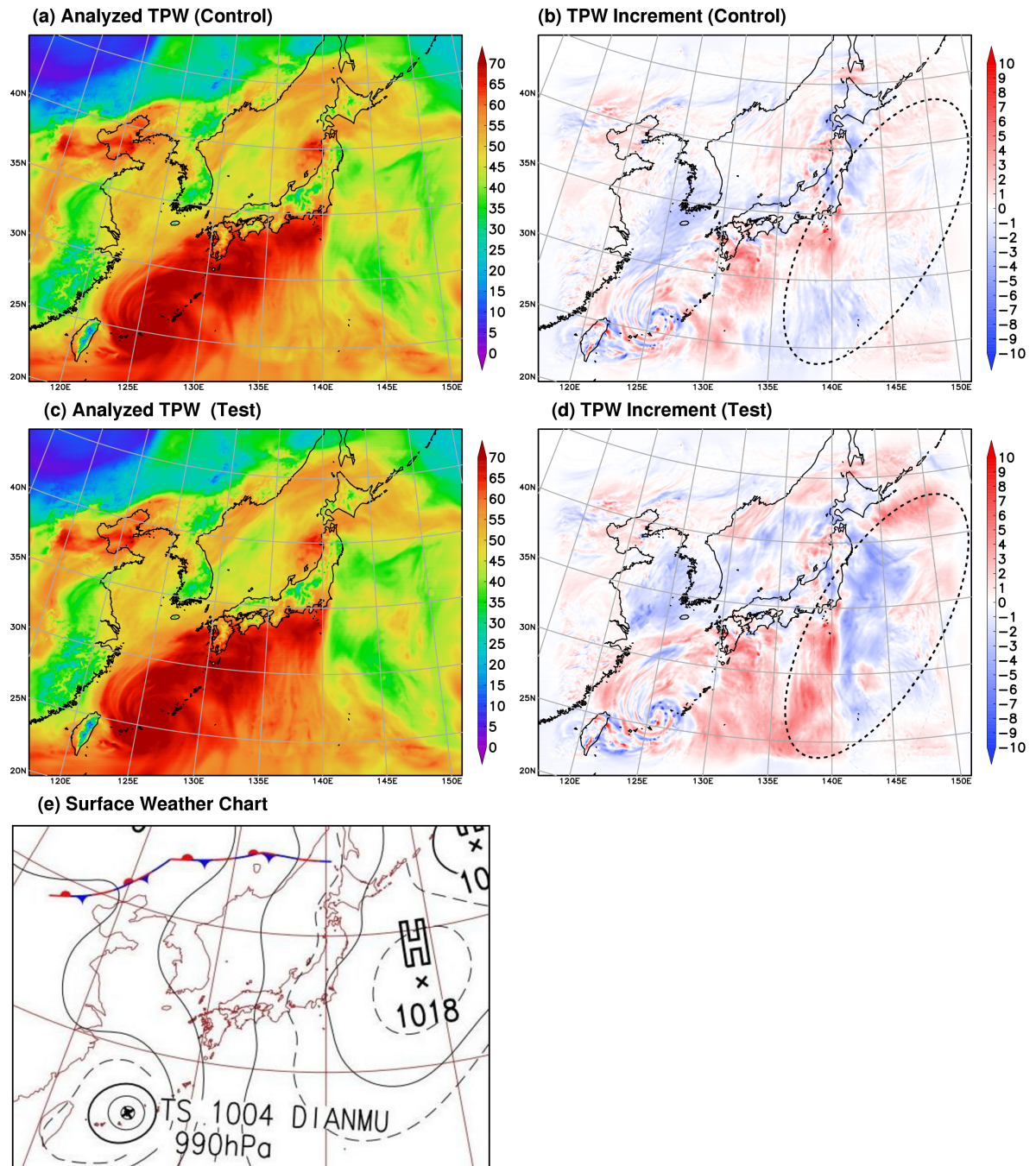


Figure 3.6. Comparison of the analyzed TPW field and the TPW analysis increment at 0000 UTC 9 Aug 2010, in the Test and Control runs. Shown on the left are the analyzed TPWs for the (a) Control and (c) Test runs. Shown on the right are the analysis increments for the (b) Control and (d) Test runs. The units are mm. (e) The surface weather chart at 0000 UTC 9 Aug 2010. Dotted lines in (b) and (d) highlight the areas where the difference in the TPW increment is large. The relaxation area for the lateral boundary (see the text) is included at the edge of the displayed area.

Moreover, the moisture increment became seamless and consistent from the land to the open ocean (see the dotted ellipses in Figures 3.6(b),(d)). As a result, the TPW contrast along the boundary of the high pressure system was enhanced in the Test run.

Figure 3.7 compares the MTSAT-observed IR image and the simulated image from the mesoscale analysis fields at 0900 UTC 9 August 2010. The separated cloud feature located south of Japan (see red arrow in Figure 3.7(c)) was well represented in the Test run.

In a heavy rain event caused by a seasonal front, a significant difference in the analyzed TPW field was found. Figure 3.8 compares the analyzed TPW fields of the Test run and the Control run at 2100 UTC 2 July 2010. The stationary front began over China and moved to the western part of the Sea of Japan. In the Test run, the analyzed TPW in the East China Sea was larger (approximately 5 - 10 mm) than that of the Control run. The moisture flow from the southwest around Kyushu was strengthened in the Test run; the TPW exceeded 70 mm.

Figure 3.9 shows 3-h accumulated rainfall forecasts for 0300 UTC 3 July 2010 from various initialization times. The top panels in Figure 3.9 indicate the rainfall forecasts of the Control run and the middle panels indicate those of the Test run. The initial times are 2100, 1500, and 0900 UTC 2 July 2010, from the left side, corresponding to 6-, 12- and 18-h forecasts, respectively. The bottom panel in Figure 3.9 indicates the rainfall distribution from radar observations, which are calibrated with rain gauges. A notable change was found in the 6-h rainfall forecast from the initial time of 2100 UTC 2 July 2010 (left panels in the top and middle). Strong rainfall [50 mm (3 h)^{-1}] was predicted near the south of Kyusyu and Tanegashima Island in the Test run, whereas only weak rainfall was predicted for those areas in the Control run. The predicted rainfall differences for other forecast periods were less than the 6-h rainfall forecast difference. The improvement of the rainfall forecast was outstanding for short-term forecasting, suggesting that the TPW difference and the southwest moisture flow over the ocean, shown in Figure 3.8, enabled the rainfall forecast to be more realistic.

Figure 3.10 shows the bias scores and threat scores of the 3-h cumulative rainfall forecasts for the Control and Test runs from three experiment periods. The definitions of the scores are described in Appendix A. Each panel shows the scores at different thresholds within a 10-km grid box. Generally, the results show that the Test run outperforms the Control run for both scores.

3.4. Data-denial Experiment for Typhoon Roke in 2011

3.4.1. Experimental Configuration

To investigate the individual radiance data's contribution to the mesoscale analyses and forecasts, several data-denial experiments were performed. Typhoon Roke in 2011 was selected for this case study. As shown in Figure 3.11, Roke became a tropical storm near the south boundary of the mesoscale model domain at 0600 UTC 13 September 2011 and proceeded westward, approaching Daito Islands on 16 September. The typhoon moved slowly in a counterclockwise direction, making a circular track west of Minami-Daito Island. The typhoon

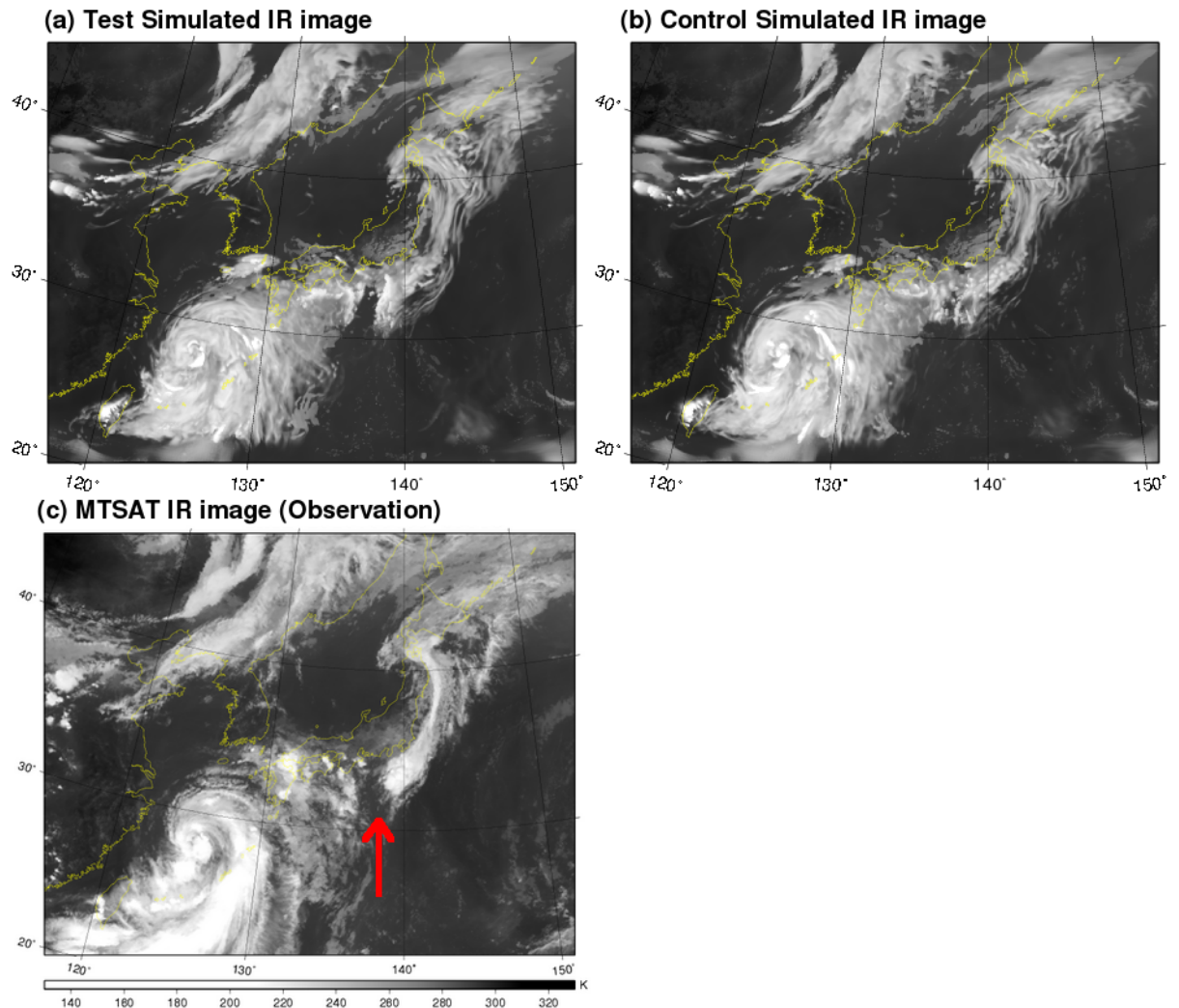
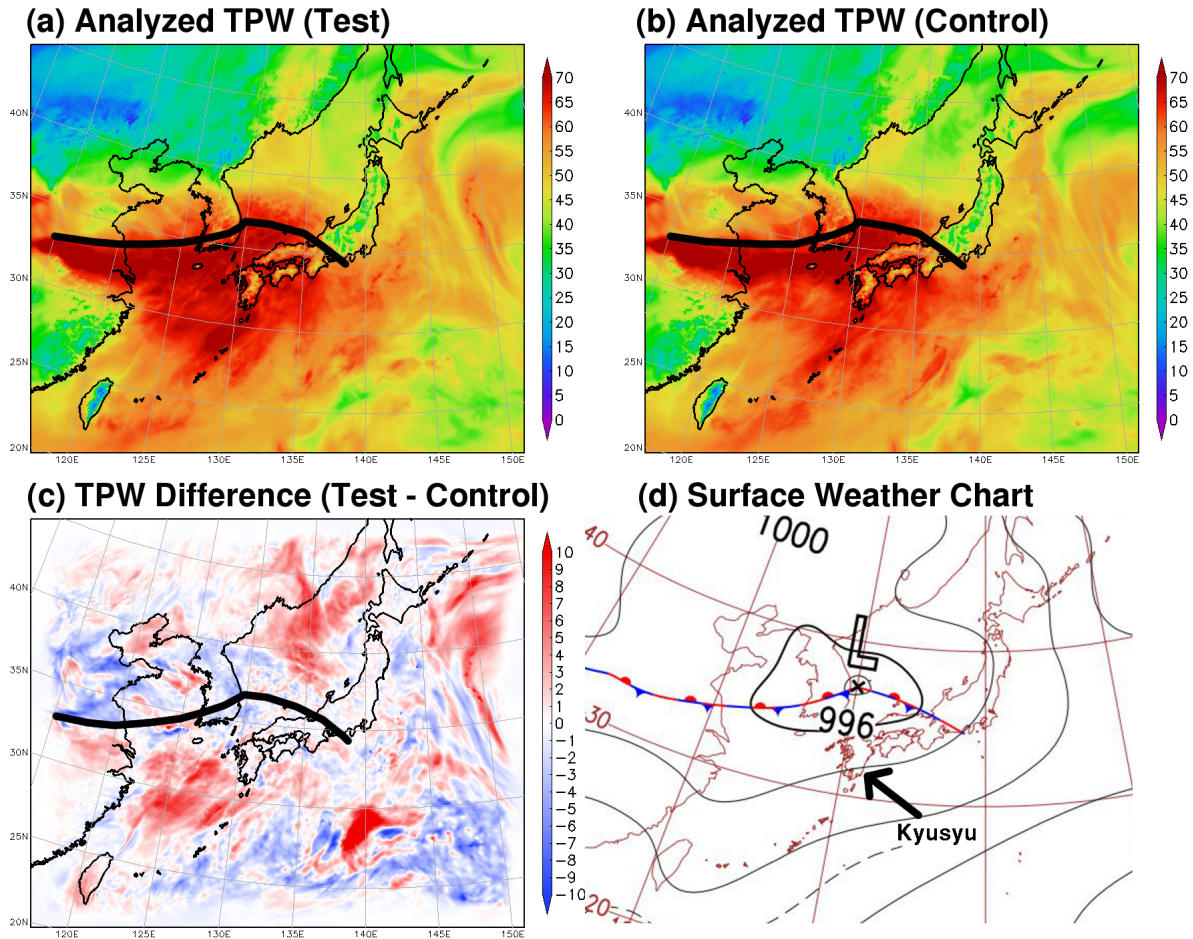


Figure 3.7. Comparison of MTSAT-observed IR image (IR1, $10.3 - 11.3 \mu\text{m}$) and the simulated image from the mesoscale analysis field at 0900 UTC 9 Aug 2010. The simulated IR imagery from the (a) Test and (b) Control runs. (c) The observed IR image. The relaxation area for the lateral boundary (see the text) is included at the edge of the displayed area. The cloud discussed in the text is indicated with a red arrow in (c).



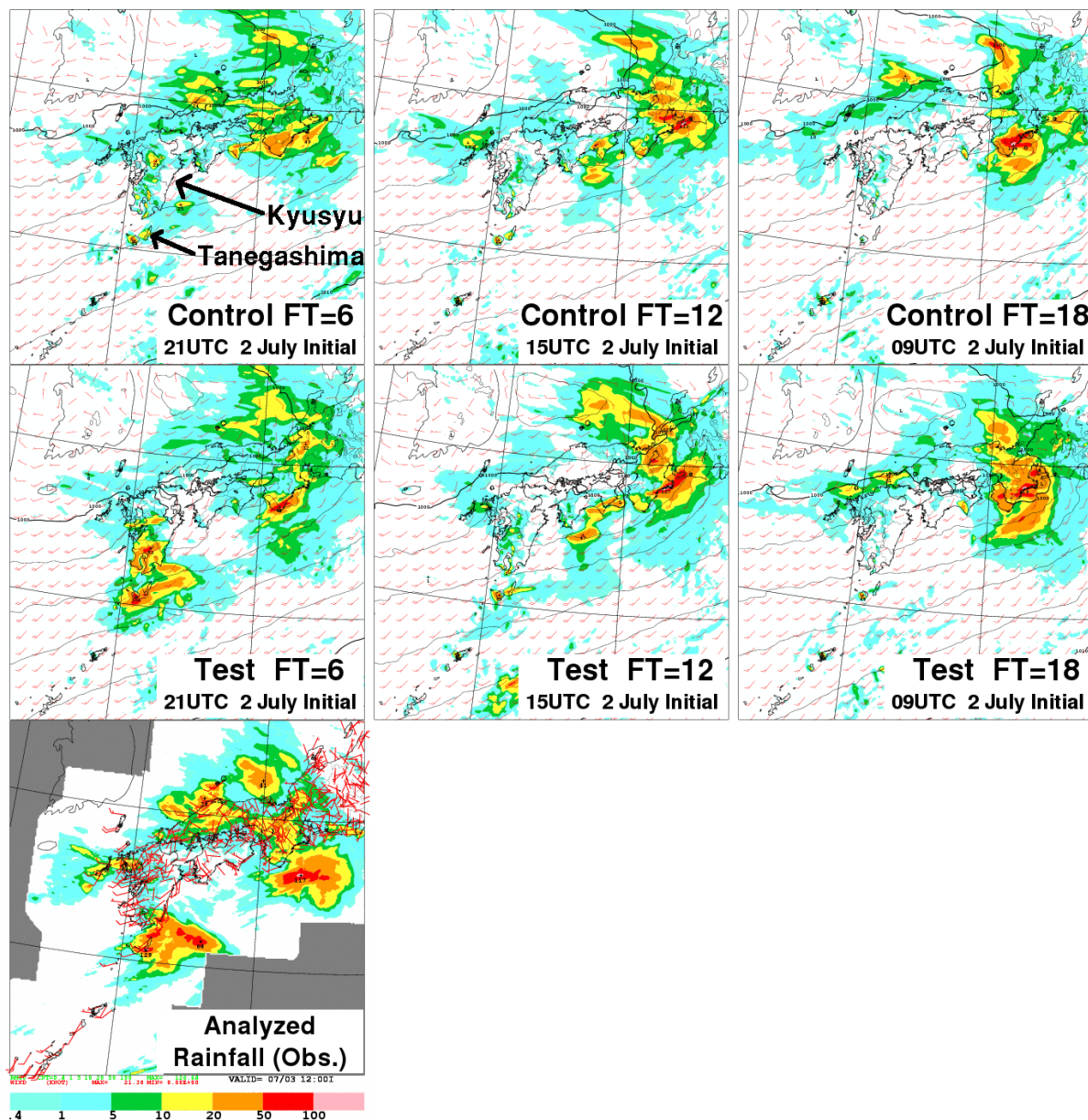


Figure 3.9. Comparison of the 3-h accumulated rainfall forecast for 0300 UTC 3 Jul 2010, from different initialization times. The rainfall forecasts of the (top) Control and (middle) Test runs. The initial times are 2100, 1500, and 0900 UTC 2 Jul 2010, from the left side, corresponding to 6-, 12-, and 18-h forecasts, respectively. (bottom) The rainfall distribution estimated from radar observations and rain gauges. The units are mm. The locations of Kyusyu and Tanegashima Islands are shown in the top-left panel.

3.4. DATA-DENIAL EXPERIMENT FOR TYPHOON ROKE IN 2011

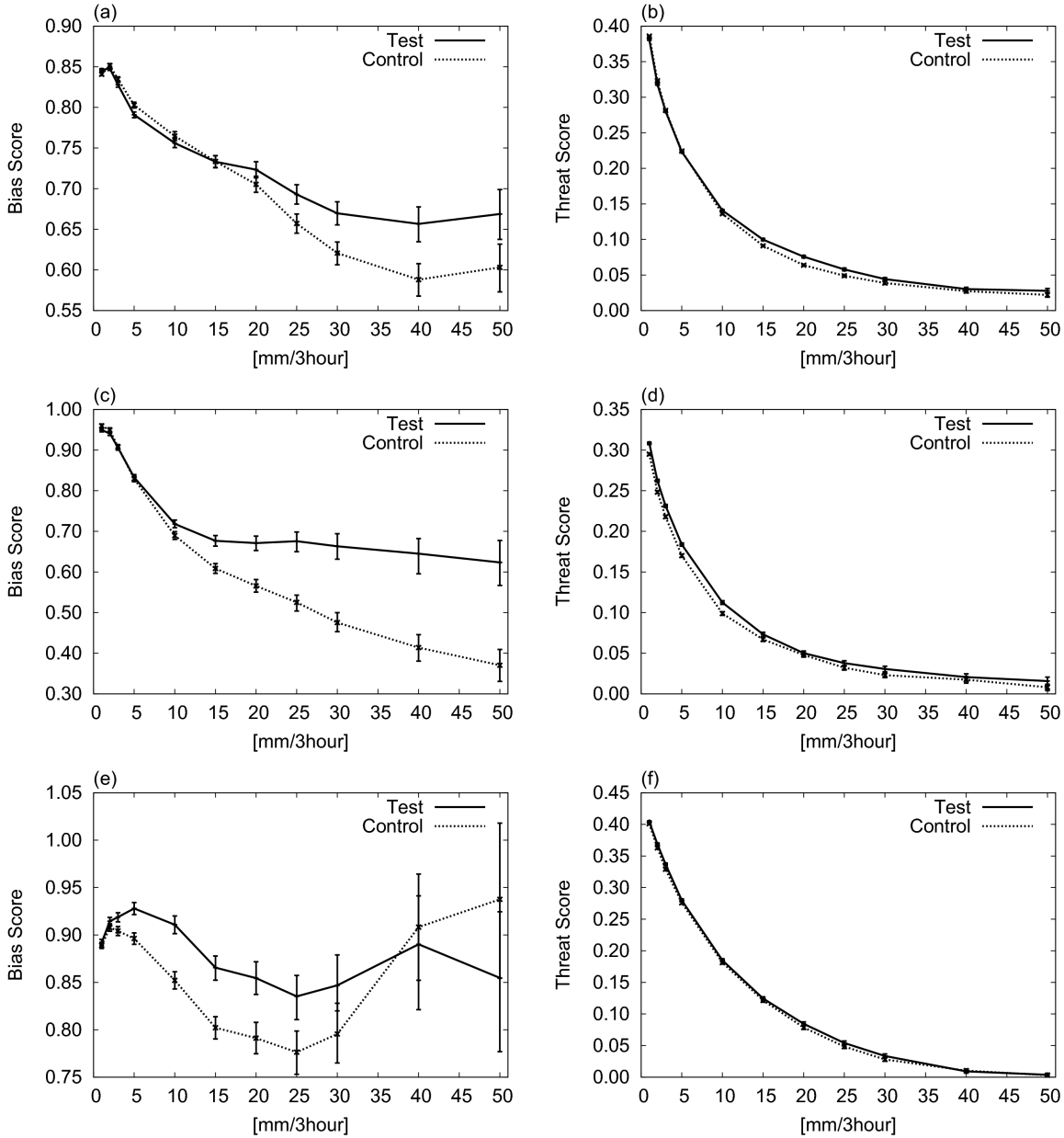


Figure 3.10. (a) Bias scores and (b) threat scores of 3-h cumulative rainfall from the Test (solid line) and the Control (dotted line) runs from 16 to 26 Jul 2009. (c), (d) As in (a), (b), respectively, but from 1 to 5 Jul 2010. (e), (f) As in (a), (b), respectively, but from 9 to 12 Aug 2010. The horizontal axis indicates the threshold $[\text{mm}/(3 \text{ h})^{-1}]$ in the score calculations. The grid size of the score calculation is 10 km.

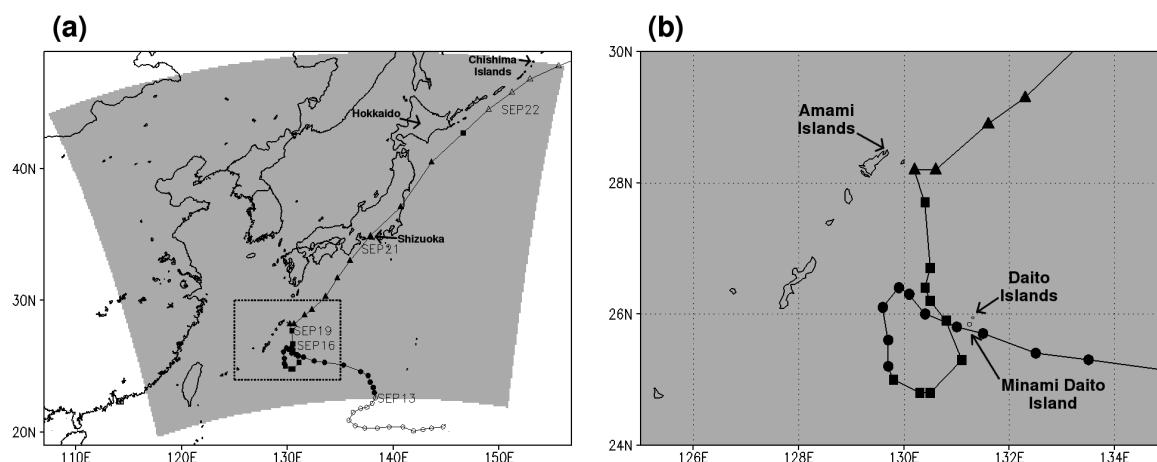


Figure 3.11. (a) The “best track” of Typhoon Roke provided by the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon Center. The JMA mesoscale model domain is shown in gray. Roke’s center is plotted every 6-h with the following symbols: open circles, tropical depression; filled circles, tropical storm; squares, severe tropical storm; filled triangles, typhoon; and open triangles, extra-tropical cyclone. (b) Enlarged view of the dotted rectangle area in (a). The dates and the location names are shown.

moved to the north toward the southeast of the Amami Islands and strengthened to a severe tropical storm with a 35 m s^{-1} maximum wind speed at 1200 UTC 19 September. The wind increased to a maximum of 50 m s^{-1} , and the minimum central pressure was 940 hPa. The typhoon made landfall in Shizuoka at 0500 UTC 21 September and moved to the northeast. After the landfall, the typhoon moved over the ocean to the southeast of Hokkaido and weakened around the Chishima Islands on 22 September. The typhoon came into the mesoscale model domain from the south in the early stages of its development. Because the available conventional and ground-based observation data were sparse in southern Japan compared to the coastal areas of Japan, this case is expected to clearly demonstrate the effects of the satellite radiance assimilation.

The period of the data-denial experiment was set from 13 to 22 September 2011. The analyses were performed every 3-h during the period and 33-h forecasts were made beginning at 0300, 0900, 1500, and 2100 UTC every day. Table 3.2 summarizes the experimental configuration. Here, the crisscross symbol ($\times$) signifies that the data were present. The control run has the same configuration as the JMA operational system as of June 2011. All operational observation data, including conventional data and the radiance data, were assimilated. In experiment 1, the microwave imager (AMSR-E, F-16 and F-17 SSMIS, and TMI) data (radiance and retrieved rain rate) were not assimilated. In experiment 2, the microwave temperature sounder (AMSU-A) radiance data were not assimilated. In experiment 3, the MHS radiance and the MTSAT CSR (water vapor channels) data were not assimilated. In experiment 4, all radiance data and the retrieval of rain rate from the microwave imager were removed. Except for the difference in the radiance data usage, the other components of the data assimilation system and forecast model were identical in all the experiments.

3.4. DATA-DENIAL EXPERIMENT FOR TYPHOON ROKE IN 2011

Table 3.2. The radiance data used in the data-denial experiments.

Expt	Microwave imager data (radiance and rain rate)	Microwave temperature sounder (AMSU-A) radiance	Microwave humidity sounder (MHS) radiance and CSR from MTSAT
Control	×	×	×
1		×	×
2	×		×
3	×	×	
4			

× = data present.

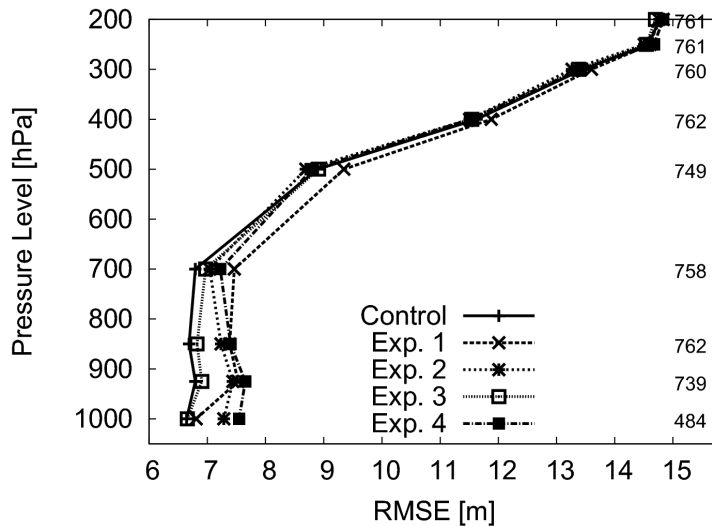


Figure 3.12. The RMSE of the geopotential height for the 3-h forecasts against the radiosonde data. The vertical axis is the pressure level (hPa) and the horizontal axis shows the RMSE (m). The statistical period was from 13 to 22 Sep 2011.

3.4.2. Verification of Analyzed Fields against Radiosonde Data

The majority of the significant differences in the analyzed fields were found in the lower troposphere below 500 hPa. Figure 3.12 shows the RMSE of the 3-h forecast of the geopotential height against the radiosonde. The Control run RMSE was the best and that of experiment 4 (with no radiance data) was the worst. Additionally, the degradation in experiment 3 (no MHS and no CSR) was relatively small compared to the other cases. The large degradation of RMSEs for the geopotential height in the lower troposphere in experiments 1 and 2 indicates that the temperature and humidity information from AMSU-A and the microwave imagers substantially contributed to the accuracy of the analysis and the short-range forecasts.

3.4.3. Impact on Precipitation Forecast

In the 4DVAR analysis, precipitation is calculated in the final outer loop step with the high-resolution mesoscale model (the horizontal resolution is 5 km). Figure 3.13 shows comparisons of the distributions of the 3-h accumulated precipitation at the analysis time (2100 UTC 15 September 2011). Strong rain areas were located over land, near the coastline of Kyushu Island, and around the core of the typhoon. Additionally, the typhoon exhibited several outer bands of rain around its center. Generally, the removal of the radiance data broadened the weak rain [$1 - 5 \text{ mm (3 h)}^{-1}$] area around the typhoon compared with the Control run, whereas the differences in the strong rain distribution at the core of the typhoon over the land and coastal areas were small. Figure 3.13(g) shows the observed hourly rainfall intensity from the TRMM satellite (TMI L2A12 version 7 product, available on-line from the Goddard Earth Sciences Data and Information Services Center website: <http://disc.sci.gsfc.nasa.gov/>). The broad weak precipitation area observed in experiment 4 (Figure 3.13(d)) did not exist in the rain-bands in the TMI-observed rain distribution. This suggests the Control run precipitation forecast (Figure 3.13(e)) is similar to reality. Moreover, the radiance assimilation can improve weak precipitation forecasts. The statistical precipitation forecast scores also support the advantages of the radiance assimilation. Figure 3.14 presents the bias scores and threat scores for each of the runs against the analyzed radar precipitation. Figure 3.14(a) and Figure 3.14(b) show the bias scores and the threat scores, respectively, with the 5 mm (3 h)^{-1} threshold. Figure 3.14(c) and 3.14(d) present identical scores but for the 40 mm (3 h)^{-1} threshold. The results shown in Figures 3.14(a), (c) clearly show that the mesoscale model has spin-up issues in the precipitation forecast for very short-range forecasts (0 – 18 h) in both threshold conditions. The radiance assimilation improves the precipitation spin-up issues (i.e., increases the precipitation) with weak precipitation [$0 - 15 \text{ mm (3 h)}^{-1}$] in the short-range forecast. For the heavy rain cases (Figures 3.14(c),(d)), the effects of the radiance assimilation were small. The scores for Figures 3.14(a), (b) also suggest that the effect of the radiance assimilation persists for at least 24 h (approximately) into the precipitation forecasts. The typhoon track and intensity forecasts were evaluated (Figure 3.15). The difference between experiment 4 (no radiance) and the Control was small. Moreover, differences between experiment 1 – 4 were also small (not shown). Use of the radiance data had less effect on the typhoon track and intensity forecasts. Because the number of samples was not sufficient for statistical significance, it is difficult to assign a general trend to the effect of the radiance assimilation on the typhoon forecast.

3.5. Discussion

In this study, a radiance assimilation scheme for a regional model was developed, and the impact of satellite-radiance assimilation was investigated with the JMA mesoscale 4DVAR system. For the radiance assimilation in the regional model, a bias correction method has not been established because of the difficulties in estimating the radiance bias in the limited regions and times. To overcome these difficulties, the radiance assimilation scheme used in the

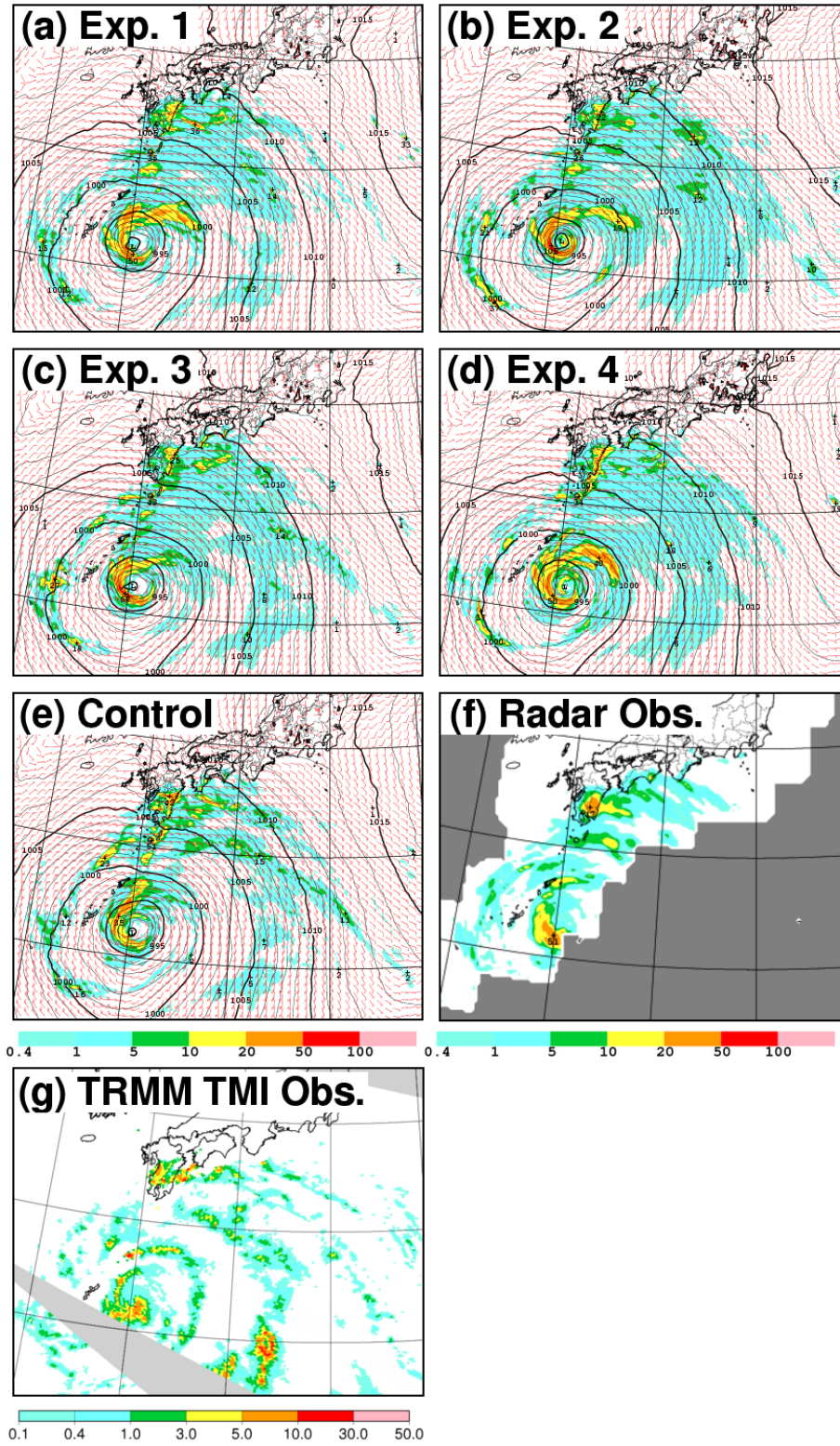


Figure 3.13. Analyzed 3-h accumulated rainfall in mm at 2100 UTC 15 Sep 2011 for (a) experiment 1, (b) experiment 2, (c) experiment 3, (d) experiment 4, (e) the Control run, and (f) radar observations. The units are $[\text{mm} (3 \text{ h})^{-1}]$. (f) TMI precipitation observations at 2000 UTC 15 Sep 2011 are also shown. The units are mm h^{-1} .

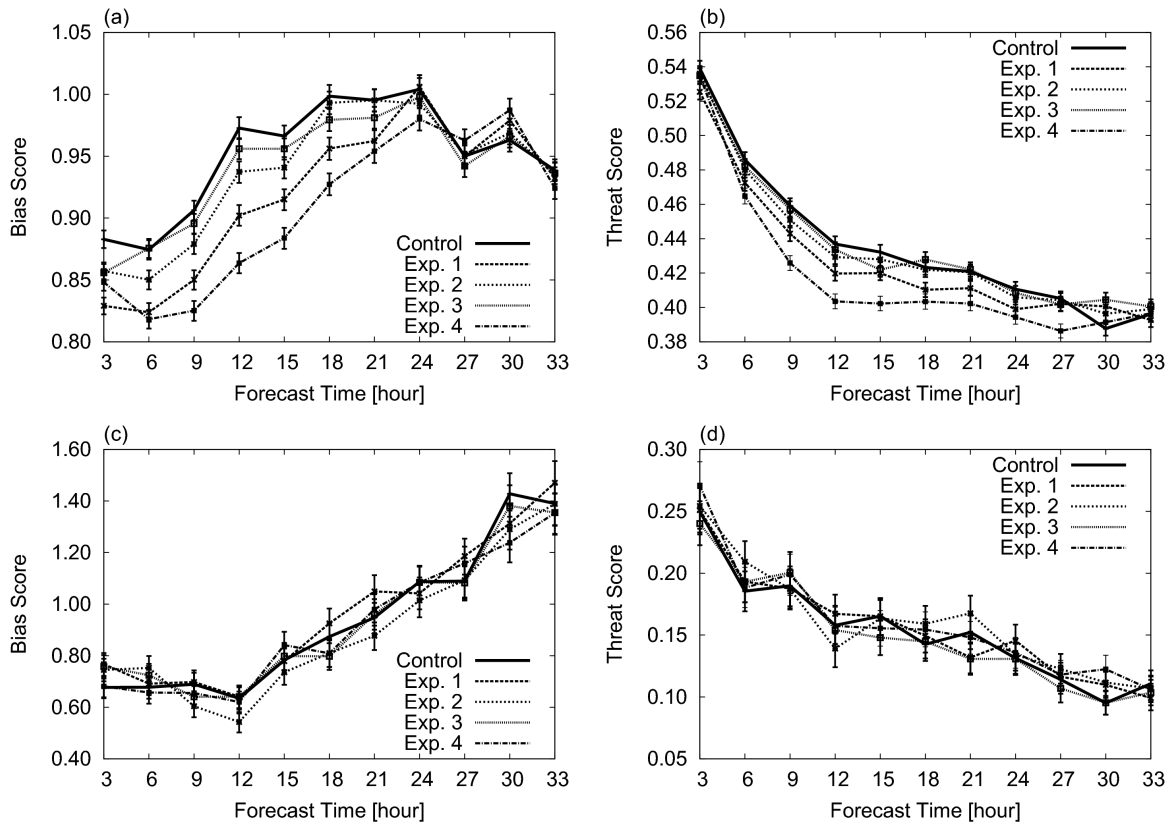


Figure 3.14. Precipitation forecast score against analyzed radar precipitation. (a) Bias score with a 5 mm (3 h)^{-1} threshold, (b) threat score with a 5 mm (3 h)^{-1} threshold, (c) bias score with a 40 mm (3 h)^{-1} threshold, and (d) the threat score with a 40 mm (3 h)^{-1} threshold. The grid size of the score calculation is 10 km.

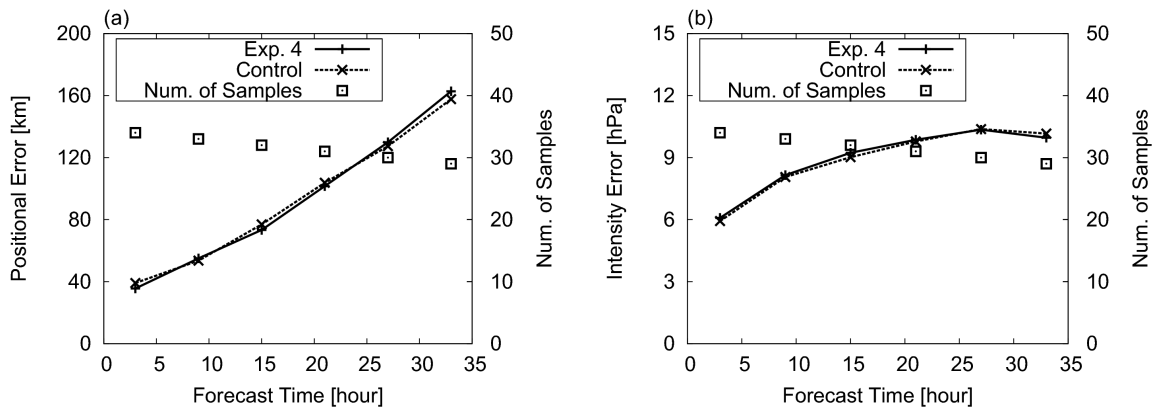


Figure 3.15. The verification of the typhoon track and intensity forecasts. (a) Positional error and (b) intensity error against the best track of Typhoon Roke provided by the RSMC Tokyo-Typhoon Center.

global system was applied in the mesoscale system. The data-thinning distance was shortened to better represent the high resolution mesoscale model, and the atmospheric profiles were extrapolated from the mesoscale model top to the radiative transfer model top. Moreover, the bias coefficients estimated in the global system were adopted. It is confirmed that the profile extrapolation is necessary to reduce the radiance biases from the comparison of O - B departures, allowing us to effectively use the radiance data in the mesoscale system in the same way as in the global system. This result suggests that most of the radiance biases are related to satellite sensors and the radiative transfer model origin. The dominant fraction of the O - B departure biases come from the satellite instrument and the error in the radiative transfer model origin. The effect of using a different first-guess profile (the mesoscale model or the global model) in the radiative transfer calculation is relatively small because the bias-corrected O - B departure in Figure 3.4 shows less bias. Therefore, the coefficients estimated in the global system represent a general trend in the radiance biases, and their use in the mesoscale system is acceptable in this initial implementation of the radiance assimilation scheme. However, the assumption that the profiles from the two models can be treated equally might not be valid for some situations. This is a topic of future research. Updating the coefficients using the past O - B departure statistics inside the mesoscale analysis is one idea for the estimation of the biases in the mesoscale analysis system (daily or weekly updates to the coefficient).

In the assimilation experiments, the direct use of the radiance data and the addition of new satellite radiance data demonstrated considerable positive effects on the mid- and lower-tropospheric geopotential height forecasts versus the retrieval assimilation. A reduction in the RMSE of the geopotential height forecast was confirmed with radiosonde observations. The reason for the large forecast improvements in $FT = 3$ and $FT = 15$ is believed to be related to the introduction of the radiance data into the data-sparse analysis time. The use of radiance data and the addition of the radiance data from the new satellite filled the gap and complemented the lack of the observation information from the conventional observation network. AMSU-A radiance data assimilation and the use of radiance over land, where only channels sensitive to higher-level atmospheric temperature are assimilated, are believed to have been the primary contributors to this improvement. Similar unbalanced observation effects that depend on analysis time were reported in Zapotocny et al. (2005). Assimilation of the radiances from various microwave imagers, humidity sounders, and MTSAT CSR produced realistic tropospheric moisture fields.

The simulated MTSAT infrared image from the analysis in the radiance assimilation showed similar features to the real MTSAT image. This result suggests that the analyzed tropospheric moisture field and the hydrometeors produced in the 4DVAR analysis in the Test run became more realistic than they were in the Control run.

Together, these findings demonstrated that the satellite data contribution to the analyses and forecast accuracy in the JMA mesoscale analysis was greater than the contribution of the previous retrieval assimilation stage because much of the satellite radiance data were assimilated into the analysis. The verification of the geopotential height forecast with the radiosonde data implies that much of the satellite dataset is necessary to maintain the accuracy of the analysis and forecasts in the operational NWP system.

Based on these findings, the radiance assimilation was introduced in the JMA mesoscale 4DVAR system on 13 December 2010. The radiance assimilation allowed for the early introduction of radiance data into the operational system. After the implementation of the radiance assimilation scheme in the JMA mesoscale system, DMSP F-18 SSMIS radiance data were incorporated into the system on 6 December 2011.

Furthermore, to clarify the contribution of the radiance data (or sensor type) to the analysis and forecast, several data-denial experiments were performed in association with Typhoon Roke. One possible reason for the minor impact on the typhoon track forecasts is that the typhoon track forecast was strongly affected by large-scale meteorological conditions (i.e., the location of a high pressure system and upper-level jet). Most of these conditions are determined by the lateral boundary conditions (Warner et al., 1997).

Improving the analyzed fields with radiance assimilation in the regional model domain may not directly contribute to improving typhoon track forecasting for short-range forecasting. In a recent study on microwave radiance assimilation using a limited-area ensemble data assimilation system (Schwartz et al., 2012), improvements in precipitation forecasts caused by a tropical cyclone were reported. However, no significant positive impact on the track forecast was found.

Although the radiance assimilation brought improvements in the forecast of the geopotential height and precipitation over the ocean, the major effects on precipitation forecasts were limited to the ocean and in light precipitation areas. Because the rain-rate data from ground-based radars were assimilated in the experiments, the precipitation over the land exhibited similar features. The impact of the radiance assimilation was limited over the ocean because the surface-sensitive radiances over the land and the rain-affected radiances have not yet been assimilated into the current JMA systems. Cloud- and rain-affected radiance assimilation schemes for the JMA system are under development (Kazumori et al., 2010). In the current JMA system, the radiance data strongly constrain the temperature and moisture fields only in clear and non-precipitation areas; the contribution in cloudy areas, in rainy areas, and over land is relatively weak in the analysis.

Zou et al. (2011) also reported that the assimilation of the Geostationary Operational Environmental Satellites-11 and -12 (GOES-11/12) radiances under preconvective conditions improved quantitative precipitation forecasts in a 3DVAR system with a limited-area model. The radiance assimilation of the clear-sky conditions is a necessary step toward advanced cloud- and rain affected radiance assimilation in the JMA mesoscale system.

The assimilation of cloud- and rain-affected radiance near the typhoon core and of surface-sensitive channels over land are expected to bring further improvements in precipitation forecasts. Finally, Kawabata et al. (2011) reported that high-frequency ground-based radar reflectivity assimilation can reproduce a heavy rain event. The assimilation of high-frequency and high-density radiance data from future geostationary satellites will be next research topic. Moreover, issues related to the optimal data-thinning distance and the correlated observation errors must be investigated.

4. Impact Study of AMSR-E Radiances in the NCEP Global Data Assimilation System

4.1. Introduction

Since 2002, the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) has been observing the atmosphere and surface of the earth using vertically and horizontally polarized radiation at six microwave frequencies from 6.925 to 89 GHz. Other microwave imagers, such as the Special Sensor Microwave Imager (SSM/I) and Special Sensor Microwave Imager Sounder (SSM/IS), use almost identical channels in the microwave range, from 19 to 91 GHz. In addition to these channels, AMSR-E has four low frequency channels in the microwave range (6.925 and 10.65 GHz, dual polarization) that are sensitive to the sea surface wind speed and the sea surface temperature, and are less affected by the atmosphere. Therefore, these measurements provide useful information on the sea surface wind speed and sea surface temperature under almost all weather conditions. The Japan Meteorological Agency (JMA) has been using AMSR-E radiance data in their global data assimilation system since May 2006, and they found it has improved typhoon track predictions and rainfall forecasts (Sato, 2006b). The purpose of this study is to examine the impact of AMSR-E radiances, including the low frequency channels, in the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS).

The NCEP GDAS makes use of passive microwave satellite measurements (Derber and Wu, 1998; Okamoto and Derber, 2006) to improve the accuracy of atmospheric analyses and forecasts. An accurate microwave ocean emissivity model is necessary to assimilate surface sensitive microwave radiances over the ocean. In this study, a scheme to assimilate AMSR-E radiances into the NCEP GDAS is developed, which includes a new microwave ocean emissivity model for AMSR-E low frequency radiances. The assimilation of AMSR-E radiances is expected to have some impacts on the lower troposphere and sea surface in the analyses, as well as on the atmosphere in the forecasts. The impacts of AMSR-E radiance assimilation on the NCEP analyses and forecasts are examined.

In section 4.2, description of the microwave ocean emissivity models developed for this study is provided and the basis for the new microwave ocean emissivity model is presented. Comparisons of satellite brightness temperature measurements versus calculated values using the emissivity model and the NCEP operational emissivity model [FAST Emissivity Model,

version 1 (FASTEM-1; English and Hewison (1998)] are shown in section 4.3. A sensitivity analysis for the microwave ocean emissivity models is shown in section 4.4. Assimilation experiments examining the impact of AMSR-E radiances are shown in section 4.5, and the summary is presented in section 4.6.

4.2. Microwave Ocean Emissivity Model

4.2.1. Overview

The Community Radiative Transfer Model (CRTM; Weng et al., 2005) previously in the NCEP GDAS used a FASTEM that was the same as the one included in the Radiative Transfer for Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (RTTOV), version 6 (Saunders, 2000). The FASTEM is similar to FASTEM-1, but the FASTEM has a bug in the calculation of permittivity that affects the emissivity model performance for low frequency channels. Therefore, FASTEM-1 code was obtained from the model developer and used it for the comparisons in this study.

FASTEM-1 assumes specular reflection and calculates the reflectivity from surface properties (e.g., sea surface temperature, 10-m wind speed). However, FASTEM-2 and -3 use atmospheric transmittance as an input parameter for an effective path correction, which is made during the computation of the down-welling brightness temperature (Deblonde, 2000), effectively taking into account non-specular reflection. The current CRTM does not use atmospheric transmittance as an input for the surface optics calculation. Therefore, it is difficult to use FASTEM-2 (or -3) in the current CRTM. Using FASTEM-2 (or -3) in combination with the CRTM for an impact study in NCEP GDAS is a very interesting topic but is beyond the scope of the AMSR-E impact study.

FASTEM-1 is a semi empirical model, with good performance in the Advanced Microwave Sounding Unit (AMSU) A/B and SSM/I frequency range. However, as shown in section 4.3, FASTEM-1 has significant errors in the calculation of microwave emissivity at low frequencies (e.g., 6.925 and 10.65 GHz horizontally polarized channels of AMSR-E). Therefore, to assimilate AMSR-E low frequency channel radiances effectively in the current NCEP GDAS, the development of a new microwave ocean emissivity model is necessary.

A new microwave ocean emissivity model is developed by empirically fitting known physical constraints on the ocean surface emission to the measurements of satellite instruments. The following sections describe the details of this new microwave ocean emissivity model and its derivation. Currently, azimuth angle dependence is not considered in the new model. Biases of calculated radiance related to surface wind speed are primary research target in this study. Actually, vertical and horizontal polarized radiances from AMSR-E have azimuthal variation, especially, in high surface wind condition. Impact of taking the azimuth variation into account in the emissivity modeling is investigated in depth in Chapter 5. When the full Stokes (Liou, 2002) measurements are used (such as WindSat on Coriolis) the consideration of azimuth angle dependence, including third and fourth Stokes parameter calculations, is required. They

are beyond the scope of this thesis. Furthermore, AMSR-E low frequency channels are affected by Radio Frequency Interference (RFI). These RFI spots are observed worldwide but seem to be minuscule over the oceans, except near some islands (JAXA, 2004).

4.2.2. Ocean Surface Roughness

Microwave ocean emissivity depends on the ocean surface roughness resulting from surface waves that are generated by wind. In this study, a simple two-scale model for the ocean surface roughness is used. In the two-scale model, a small-scale wave (capillary wave) and a large-scale wave (gravity wave) are used to characterize the complete wave spectrum. The two-scale ocean roughness approximation is commonly used in ocean emissivity models (e.g., Wentz, 1975; Wu and Fung, 1972) and has shown sufficient accuracy against ground-based and aircraft measurements.

When the wind starts blowing, it makes small ripples on the ocean surface. The height variance ζ is given by

$$\zeta^2 = \int_0^\infty S(K) dK, \quad (4.1)$$

where K is wave number and $S(K)$ is an ocean roughness spectrum function.

The two-scale approach, which separates the waves into large and small scales, is a convenient approximation. A cutoff wave number is used for the separation. The method of Liu et al. (1998) defines the small-scale wave as being much smaller than the electromagnetic wave of incident radiation, with the small-scale waves existing on the large-scale wave. The ocean wave spectrum from Bjerkaas and Riedel (1979) is used to define an ocean wave spectrum independent of azimuth angle.

The reflectivity is decreased by the diffraction effect by the small-scale waves. To account for this diffraction effect, the reflectivity is multiplied by the modified Fresnel coefficient (Guissard and Sobieski, 1987):

$$|R_p^2| = |R_{p,\text{Fresnel}}|^2 \exp(-4k^2 \zeta_R^2 \cos^2 \theta), \quad (p = h \text{ or } v), \quad (4.2)$$

where ζ_R is the small-scale height variance and $k (= 2\pi\nu c^{-1})$ is the wave number of electromagnetic radiation; c is the speed of light. This equation is correspond to Eq. (2.32) of FASTEM-1. An additional correction related to the large-scale waves is still required.

To separate the ocean spectrum into small and large scales, ζ_R should satisfy

$$k \zeta_R \ll 1. \quad (4.3)$$

With the introduction of the cutoff wave number K_c separating the small and large scales, to ensure that the small scale is much smaller than the large scale, K_c must satisfy

$$\frac{K_c}{k} \ll 1. \quad (4.4)$$

Assuming $k \zeta_R = K_c k^{-1}$, the small-scale height variance is written as follows:

$$\frac{K_c^2}{k^4} = \zeta_R^2 = \int_{K_c}^{\infty} S(K) dK. \quad (4.5)$$

The cutoff wave number K_c is calculated to satisfy the above equation. To reduce computational time, a look-up table for the height variance is used in the calculation.

Note that the small-scale correction is not applied to frequencies below 15 GHz. Preliminary results showed that the difference between the calculated brightness temperature and observed brightness temperature for AMSR-E became larger with the small-scale correction. It is probably not enough to consider only the diffraction effect at frequencies below 15 GHz, since penetration plays an important role in the low frequency range.

A large-scale correction term is added to represent the effect of the large-scale wave reflectivity. This term is dependent on incident angle, frequency, and wind speed:

$$|R_v|^2 = |R_{v,\text{Fresnel}}|^2 \exp(-4k^2 \zeta_R^2 \cos^2 \theta) + W_s(a_1 + a_2 \theta + a_3 \theta^2) f(\nu) \quad \text{and} \quad (4.6)$$

$$|R_h|^2 = |R_{h,\text{Fresnel}}|^2 \exp(-4k^2 \zeta_R^2 \cos^2 \theta) + W_s(b_1 + b_2 \theta + b_3 \theta^2) f(\nu), \quad (4.7)$$

where $f(\nu)$ is a function of frequency defined as follows:

$$f(\nu) = \frac{\nu}{c_1 + c_2 \nu}, \quad (4.8)$$

where $a_1, a_2, a_3, b_1, b_2, b_3, c_1$ and c_2 are constants that are derived from a fit to the satellite measurements in section 4.2.5. At the nadir ($\theta = 0$), the vertical and horizontal reflectivity are required to be the same and, thus, $a_1 = b_1$. Under this model, Eqs. (4.6) and (4.7) satisfy Fresnel's law for the calm sea. FASTEM-1 does not have this constrain in the emissivity modeling.

4.2.3. Permittivity

Effects of ocean salinity cannot be neglected below 20 GHz. To take this effect into account, the model uses Guillou's permittivity model (Guillou et al., 1998) below 20 GHz and Ellison's model (Ellison et al., 2003) above 20 GHz. There are discontinuities between Ellison et al. (2003) and Guillou et al. (1998) at 20 GHz, as shown in Figure 4.1. But the discontinuities are small when compared with the dynamic ranges of permittivity. In the assimilation experiment, the models are used for discrete frequencies rather than continuous frequencies. The discontinuities at 20 GHz do not affect this study.

4.2.4. Foam Emissivity and Foam Fraction

Stogryn (1972) derived an empirical sea foam emissivity model as a function of frequency, incidence angle, and sea surface temperature from previously published radiometric measure-

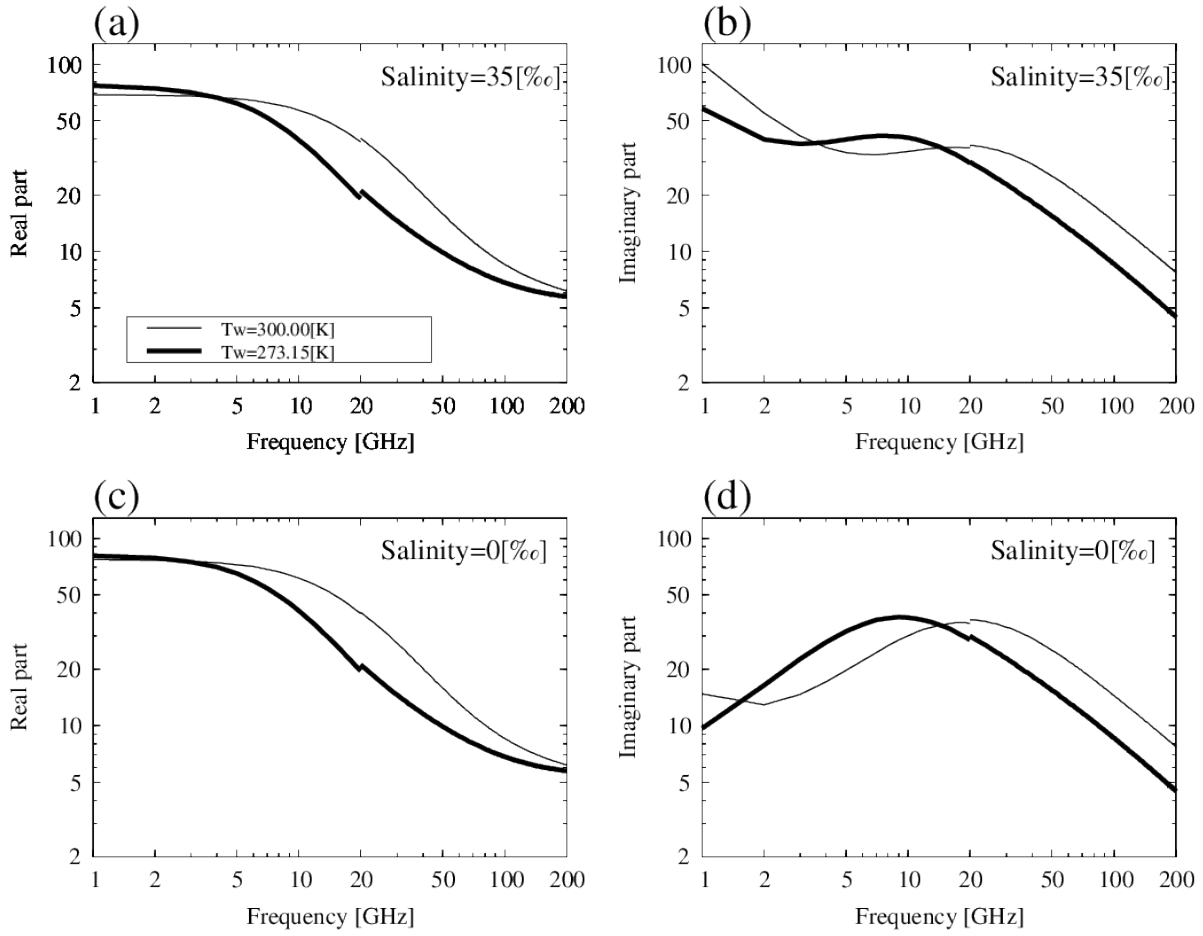


Figure 4.1. The permittivity from the Ellison et al. (2003) model (above 20 GHz) and Guillou et al. (1998) (below 20 GHz). (a), (c) The real part (salinity 35‰, and 0‰, respectively), and (b), (d) the imaginary part. Thick and thin lines are for water temperature 300.00- and 273.15-K cases, respectively.

ments as follows:

$$\varepsilon_{p,\text{Foam}}(\nu, \theta) T_w = \varepsilon_{p,\text{Foam}}(\nu, 0) T_w F_v(\theta), \quad (p = h \text{ or } v), \quad (4.9)$$

$$\varepsilon_{p,\text{Foam}}(\nu, 0) T_w = 208 + 1.29\nu, \quad (4.10)$$

$$F_h(\theta) = 1 - 1.748 \times 10^{-3}\theta - 7.336 \times 10^{-5}\theta^2 + 1.044 \times 10^{-7}\theta^3, \text{ and} \quad (4.11)$$

$$F_v(\theta) = 1 - 9.946 \times 10^{-4}\theta + 3.218 \times 10^{-5}\theta^2 - 1.187 \times 10^{-6}\theta^3 + 7 \times 10^{-20}\theta^{10}, \quad (4.12)$$

where $\varepsilon_{p,\text{Foam}}(\nu, \theta)$ is the foam emissivity, T_w is the sea surface temperature in Kelvins, ν is frequency expressed in GHz, and θ is the incidence angle in degrees.

The foam emissivity for vertical and horizontal polarizations are the same at the nadir ($\theta = 0$) because of the isotropy of the foam. An observational study by Rose et al. (2002) shows that the measurements of foam emissivity at 10.8 and 36.5 GHz are greater than Stogryn (1972) foam emissivity model calculations. According to their measurements, the measured foam emissivity is greater than 0.9 over a range of incidence angles between 30° and 60° for the vertical polarization, while the horizontally polarized emissivity is lower than the vertical polarized emissivity and gradually decreases as the incidence angle increases. Based on these new measurements of the foam emissivity, Stogryn's foam emissivity model was modified. The foam emissivity at the nadir is set to 0.93 in the new model and the constant value (0.93) is used for vertical polarization at all incidence angles. The same incident angle dependence that Stogryn (1972) derived is used for the horizontal polarization. Figure 4.2 shows the Stogryn foam emissivity and modified foam emissivity as a function of incident angle.

Several empirical models of foam fraction have been suggested. Wisler and Hollinger (1977) function is given by

$$f = 7.751 \times 10^{-6} u^{3.231}, \quad (4.13)$$

where f is foam fraction and u is the 10-m wind speed in meters per second. The foam fraction is expressed by a power law of wind speed. New emissivity model adopts the Wisler-Hollinger function with the foam fraction set to zero when wind speed is below 7 m s^{-1} . Figure 4.3 shows a comparison of the two foam fraction functions. The functions are similar below 10 m s^{-1} wind speed; however, the differences become large at high wind speed conditions.

The total reflectivity of the ocean surface $\Gamma(\nu, \theta)$ can be calculated from the foam fraction f and reflectivities of the foam-free and foam-covered parts, using

$$\Gamma_p(\nu, \theta) = f |R_{p,\text{Foam-covered}}(\nu, \theta)|^2 + (1 - f) |R_{p,\text{Foam-free}}(\nu, \theta)|^2 \quad (p = h \text{ or } v). \quad (4.14)$$

4.2.5. Emissivity Estimation from Satellite Measurements

Most emissivity models are empirically adjusted based on aircraft measurements and/or ground-based measurements. New emissivity model was empirically tuned by fitting the satellite measurements and by using the CRTM for the atmospheric radiative transfer calculations.

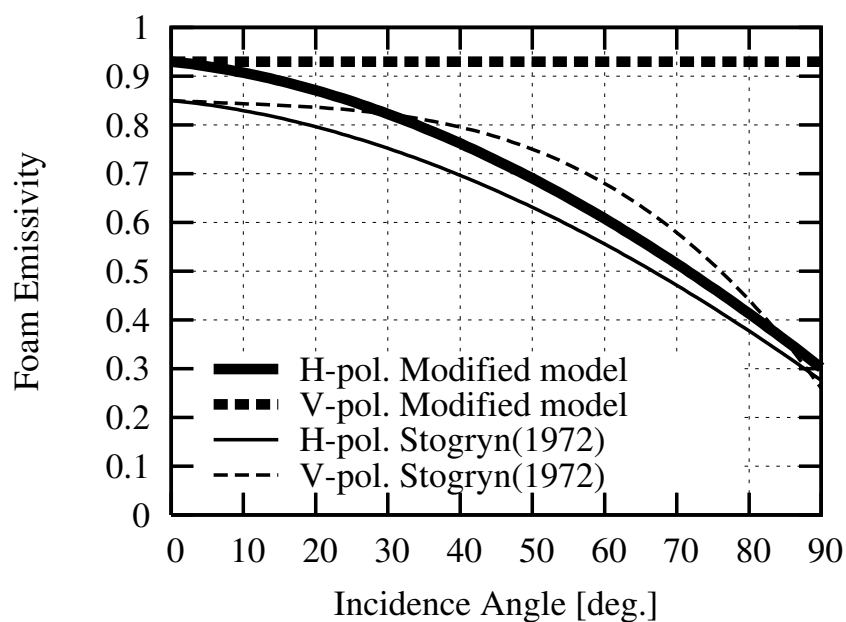


Figure 4.2. The Stogryn foam emissivity and modified foam emissivity functions (thin lines and thick lines, respectively). Solid lines are for the horizontal polarization, and broken lines are for vertical polarization. The incidence angle of AMSR-E is 55° (54.5° for 89.0 GHz).

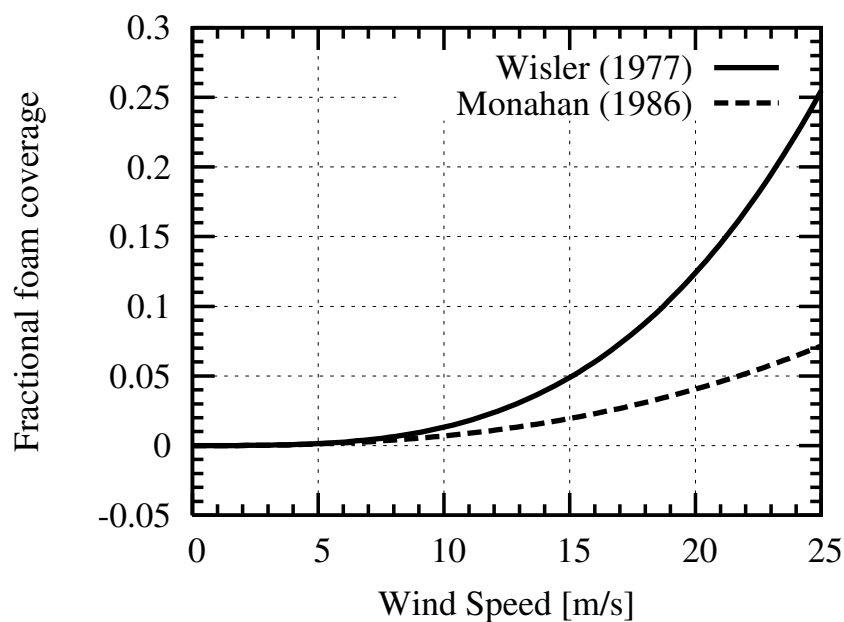


Figure 4.3. A comparison of fractional foam coverage models. The solid line is for Wisler and Hollinger (1977), which is used in the new model, and the broken line is for Monahan and O'Muircheartaigh (1986), which is used in FASTEM-1.

Table 4.1. The coefficients of the large-scale correction.

Vertical polarization		Horizontal polarization		Frequency	
a_1	2.616×10^{-5}	b_1	-2.616×10^{-5}	c_1	1.91
a_2	1.407×10^{-5}	b_2	-1.389×10^{-5}	c_2	0.12
a_3	-1.738×10^{-7}	b_3	-6.106×10^{-8}		

Based on a plane-parallel approximation (Equation (2.18), Janssen (1993)), the brightness temperature $T_b(\nu, \theta)$ at the top of atmosphere is written as

$$T_b(\nu, \theta) = T_u(\nu, \theta) + \{\epsilon_s(\nu, \theta)T_s + [1 - \epsilon_s(\nu, \theta)]T_d(\nu, \theta)\}e^{-\tau \sec \theta}, \quad (4.15)$$

where $T_u(\nu, \theta)$ is the upwelling atmospheric brightness temperature, $T_d(\nu, \theta)$ is the downwelling atmospheric brightness temperature, T_s is the surface temperature, $e^{-\tau \sec \theta}$ is the atmospheric transmittance, and ϵ_s is the ocean surface emissivity. Here $T_u(\nu, \theta)$, $T_d(\nu, \theta)$, and $e^{-\tau \sec \theta}$ are calculated by using the CRTM, and T_s is obtained from the NCEP operational SST analysis. The ocean emissivity is derived from this equation. The atmospheric input profiles for the CRTM are obtained from the operational NCEP atmosphere analysis. Microwave radiance measurements from AMSU-A on the National Oceanic and Atmospheric Administration (NOAA) satellites NOAA-15 and NOAA-16, from SSM/I on the Defense Meteorological Satellite Program (DMSP) DMSP-13, DMSP-14, and DMSP-15, and from AMSR-E on Aqua are used for the fits. Clear-sky measurements are selected based on the retrieved cloud liquid water (CLW; Grody et al., 1999; Weng and Grody, 1994; Yan and Weng, 2004). The threshold of CLW was set at 0.01 kg m^{-2} .

Mixed polarized emissivity ϵ_m can be expressed in terms of the polarization angle $\theta_{\text{polarization}}$. For vertical polarization at the nadir position, ϵ_m at scan angle θ_{scan} is

$$\epsilon_m = \cos^2 \theta_{\text{polarization}} \epsilon_v + \sin^2 \theta_{\text{polarization}} \epsilon_h, \quad (4.16)$$

where $\theta_{\text{polarization}} = \theta_{\text{scan}}$ or $\theta_{\text{polarization}} = 90 - \theta_{\text{scan}}$, depending on the polarization status at the nadir, and ϵ_v and ϵ_h are the emissivity of vertical and horizontal polarization, respectively. To include the mixed polarization of AMSU-A data in the coefficient estimation, Eq. (4.16) is used to derive the coefficients. The right-hand side of Eq. (4.16) is used as the predictor in the regression. Atmospheric profiles, surface properties of the GDAS analysis, and microwave radiance measurements from 18 December 2005 were used to derive the coefficients. The derived coefficients are summarized in Table 4.1.

4.3. Comparison of the Emissivity Models

To compare the new emissivity model (NEWMDL) and FASTEM-1, AMSR-E brightness temperatures were calculated by using CRTM and the two emissivity models. The input profiles

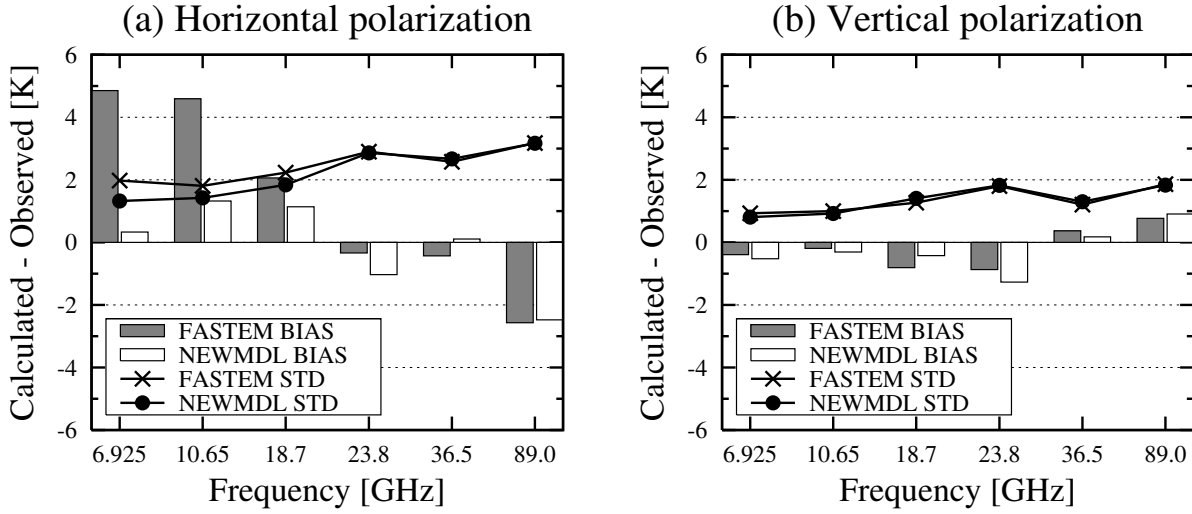


Figure 4.4. The brightness temperature comparison between the calculations and measurements of AMSR-E channels: (a) horizontal polarization and (b) vertical polarization. These statistics were calculated for the period 1 – 5 Dec 2005.

(temperature, humidity, and ozone) and surface properties (sea surface temperature and 10-m wind speed) were obtained from 6-h global forecasts of the NCEP GDAS. The emissivity models were evaluated over the period of 1 – 5 December 2005, resulting in more than 15 000 comparisons for each channel. The calculated AMSR-E brightness temperatures were compared with the measurements. Clear-sky measurements were selected using a CLW threshold of 0.01 kg m^{-2} . The bias of calculated brightness temperature (TB_{cal}) - observed brightness temperature (TB_{obs}) should be slightly negative if the cloud effect is not removed completely.

Figure 4.4 shows the results. For the horizontal polarization (Figure 4.4(a)), the biases in low frequency channels (6.925 and 10.65 GHz) are substantially reduced in the NEWMDL. At high-frequency channels, the bias and standard deviation of NEWMDL are comparable with FASTEM-1, except at 23.8 GHz. The bias of vertically polarized channels (Figure 4.4(b)) is smaller than that of horizontally polarized channels. The difference between the two models is also smaller for vertical polarization. The biases at 23.8 GHz (for both polarizations) of NEWMDL are slightly worse than those of FASTEM-1. Because these channels are located near the water vapor absorption line of the microwave frequency range, the increased bias might be caused by insufficient accuracy in the analyzed moisture field.

To understand the large differences in the biases of the horizontally polarized low frequency channels, it would be helpful to present scatter-plots of the brightness temperature difference ($TB_{\text{cal}} - TB_{\text{obs}}$) versus 10-m wind speed. The radiative transfer model (CRTM) uses atmospheric profiles (e.g., temperature, humidity, and ozone) and surface parameters (e.g., surface type, surface temperature, and surface wind speed for the ocean) as inputs for the calculation of brightness temperature. Wind speed is used for the ocean emissivity model in the CRTM and ocean emissivity determines the surface radiation in the radiative transfer calculation. Therefore, the wind speed-dependent bias in the calculated brightness temperature can

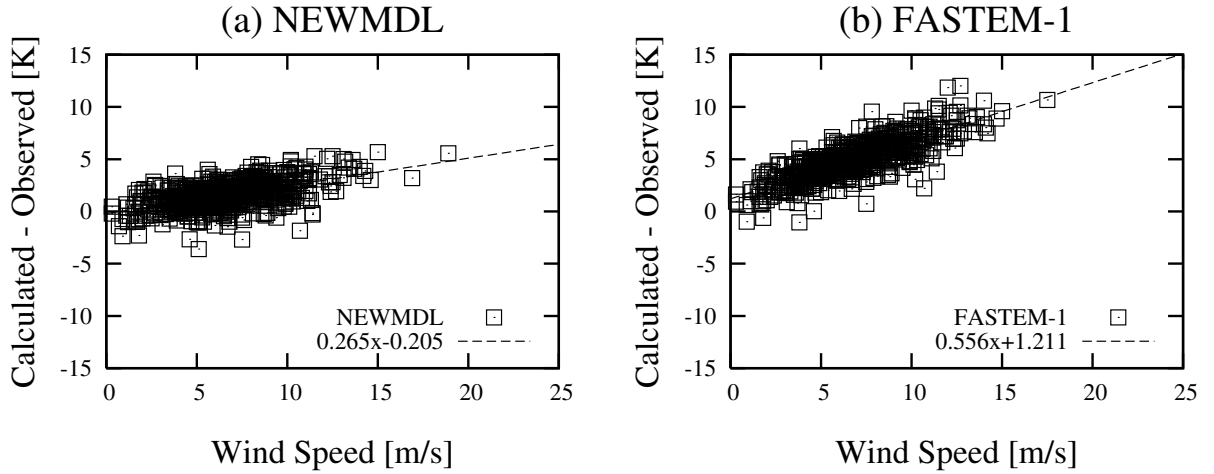


Figure 4.5. Scatter-plots of AMSR-E 10.65-GHz horizontally polarized brightness temperature difference ($T_{B_{cal}} - T_{B_{obs}}$) vs 10-m wind speed from the 6-h forecast from (a) NEWMDL and (b) FASTEM-1. The fitted linear function is also shown by the broken line in (a) and (b). These statistics were calculated from the data (total precipitable water in the range $30 - 40 \text{ kg m}^{-2}$ and SST in the range $285 - 295 \text{ K}$) for the period 1 – 5 Dec 2005.

be considered an indicator showing the performance of the ocean emissivity model. Figure 4.5 shows the scatter-plot of AMSR-E 10.65-GHz horizontal polarization for NEWMDL (Figure 4.5(a)) and FASTEM-1 (Figure 4.5(b)). Clearly, the bias increases in both models when wind speeds become large. However, NEWMDL has a smaller bias compared with FASTEM-1 at high wind speeds. Since wind speed is not a predictor in the current GSI radiance bias correction scheme (Okamoto and Derber, 2006), it is unlikely that this bias can be properly removed without improving the calculated brightness temperatures with an improved emissivity model.

4.4. Sensitivity Analysis

In this section, the sensitivity of brightness temperature to sea surface temperature and wind speed are computed for AMSR-E channels using NEWMDL and FASTEM-1. The sensitivity of the brightness temperatures to geophysical parameters is a good indicator of the available information on the geophysical parameters in that observation.

The typical sensitivity to sea surface temperature and wind speed are obtained by globally averaging all AMSR-E radiance data over the ocean from the 1200 UTC 23 October 2005 GDAS analysis. Because the foam parametrization in the emissivity models has a wind speed dependency, the data-sets are divided into two categories (wind speed at and above 7 m s^{-1} , or below 7 m s^{-1}). Table 4.2 shows the sensitivity to sea surface temperature of the AMSR-E channels, and Tables 4.3 and 4.4 show the sensitivity to sea surface wind speed. The important points from this sensitivity analysis are summarized as follows:

- The vertically polarized channels are more sensitive to sea surface temperature than the

Table 4.2. Sensitivity of AMSR-E brightness temperature to the SST for vertical polarization (V) and for horizontal polarization (H).

Frequency(GHz) polarization	NEWMDL [K K ⁻¹]		FASTEM-1 [K K ⁻¹]	
	V	H	V	H
6.925	0.56	0.26	0.54	0.26
10.65	0.46	0.20	0.43	0.20
18.7	0.23	0.07	0.19	0.05
23.8	0.11	0.00	0.11	0.00
36.5	0.01	-0.09	0.00	-0.10
89.0	0.10	-0.09	0.09	-0.10

horizontally polarized channels. The AMSR-E 6.925-GHz vertically polarized channel has the largest sensitivity to sea surface temperature. The measurements from the 6.925-GHz vertical polarization channel have more information on sea surface temperature than those from other channels. NEWMDL and FASTEM-1 have similar sensitivity to sea surface temperature for all channels.

- The horizontally polarized channels are more sensitive to surface wind speed. Generally, FASTEM-1 has a larger sensitivity to the sea surface 10-m wind speed than NEWMDL (wind speed below 7 m s⁻¹, in particular).
- The horizontally polarized channels have a larger sensitivity to surface wind speed above 7 m s⁻¹ than surface wind speed below 7 m s⁻¹ in both models.

The sensitivity to sea surface wind speed for the horizontally polarized channels may be excessive in FASTEM-1 at low frequency channels (6.925 and 10.65 GHz). Other research (Deblonde, 2000; Okamoto and Derber, 2006) has also pointed out an excess sensitivity in the SSM/I horizontally polarized channel at the lower frequency of 19 GHz.

4.5. Assimilation Experiments

4.5.1. Design of the Experiments

To examine the impact of AMSR-E radiance on analyses and forecasts, the NCEP GSI analysis system (Wu et al., 2002) and the NCEP global forecast model (as of May 2006) were employed. The operational resolution of T382L64 (wave number 382 triangular truncation with 64 vertical sigma levels) was used for these experiments. A total of 168-h forecasts were produced daily from the analysis at 0000 UTC during the experiment period. Three data assimilation experiments were conducted for one month (12 August – 11 September 2005). The three experiments include a control (Cntl) using all the operational observation data; a Test1

Table 4.3. Sensitivity of AMSR-E brightness temperature to the sea surface wind speed for $W_s < 7 \text{ m s}^{-1}$

Frequency(GHz) polarization	NEWMDL [K(m s ⁻¹) ⁻¹]		FASTEM-1 [K(m s ⁻¹) ⁻¹]	
	V	H	V	H
6.925	-0.16	0.69	0.90	0.28
10.65	-0.21	0.90	0.36	1.93
18.7	-0.43	0.68	0.05	1.33
23.8	-0.40	0.46	-0.01	0.94
36.5	-0.49	0.75	-0.11	1.33
89.0	-0.26	0.64	-0.17	0.66

Table 4.4. Sensitivity of AMSR-E brightness temperature to the sea surface wind speed for $W_s \geq 7 \text{ m s}^{-1}$.

Frequency(GHz) polarization	NEWMDL [K(m s ⁻¹) ⁻¹]		FASTEM-1 [K(m s ⁻¹) ⁻¹]	
	V	H	V	H
6.925	0.35	1.17	1.02	2.91
10.65	0.28	1.34	0.49	2.06
18.7	-0.04	1.07	0.16	1.49
23.8	-0.06	0.92	0.07	1.13
36.5	-0.14	1.17	-0.02	1.26
89.0	-0.17	0.88	-0.14	0.81

adding the AMSR-E data and using FASTEM-1; and a Test2, which is the same as Test1 except that NEWMDL is used for frequencies below 20 GHz. The operational observation dataset includes surface wind data [i.e., buoy, ship, retrieved SSM/I wind speed data, and Quick Scatterometer (QuikSCAT) wind vector data] and other microwave radiance data [AMSU-A from NOAA-15, -16, -18, and Aqua; AMSU-B from NOAA-15, -16, and -17; Microwave Sounding Unit (MSU) from NOAA-14; and Microwave Humidity Sounder (MHS) from NOAA-18], but none of those channels are below 20 GHz. Therefore, the only differences between Test1 and Test2 result from the use of NEWMDL for the AMSR-E low frequency channels. It is difficult to see a clear impact from AMSR-E if NEWMDL were applied to all microwave radiance data. Comparisons of Cntl and Test1 (and Test2) will demonstrate the impact of AMSR-E, while differences between Test1 and Test2 will show the impact of using NEWMDL with the AMSR-E low frequency channels.

The AMSR-E radiances (10.65, 18.7, 23.8, and 36.5 GHz at both polarizations) are assimilated in Test1 and Test2. The 6.925-GHz channels are not used because the size of the field of view (FOV; $43.2 \text{ km} \times 75.4 \text{ km}$) is much larger than the resolution of the analysis field (about 50 km). The AMSR-E 89-GHz channel has two scans (Kawanishi et al., 2003), 89-GHz-A and 89-GHz-B. The 89-GHz-B scan uses a different off-nadir angle resulting in a different observation location. Therefore, assimilating the 89-GHz-B channel together with other channels is difficult. The 89-GHz-A scan data were not available for the both experiment periods due to instrument trouble.

4.5.2. Quality Control of AMSR-E Radiances

Because of the huge volume of raw AMSR-E data and the difficulty of explicitly treating observation error correlations for time and space in a data assimilation system, data thinning is a convenient method for selecting the proper data for the assimilation. AMSR-E data are thinned to $160 \text{ km} \times 160 \text{ km}$ boxes over the oceans. The cloud- and rain-affected AMSR-E radiances are excluded in the quality control procedures. Although the CRTM has an ability to simulate cloudy radiances, the quality of the cloud/rain simulations is uncertain and the proper techniques for using these data are still under development.

To detect the presence of rain and cloud, the same method as in SSM/I quality control (Okamoto and Derber, 2006) was used. Rejection criteria were set based on the amount of CLW (Yan and Weng, 2004) for each channel (Table 4.5). For the low frequency channels, the thresholds are higher than for high-frequency channels because the higher-frequency channels are more sensitive to cloud. The observation errors of AMSR-E channels were set at $2/3$ of the standard deviation of $TB_{\text{cal}} - TB_{\text{obs}}$ (Okamoto and Derber, 2006). These values were calculated from the 1 – 5 December 2005 dataset and are listed in Table 4.5. As the size of the FOV of AMSR-E low frequency channels is relatively large compared to the high-frequency channels, the size of the FOV should be taken into account in the AMSR-E data processing to screen the contamination of cloud or land (ice) in the FOV. The small-size FOV data (36.5-GHz channels) inside the large-size FOV data (10.65-GHz channels) are used to detect cloud or land contamination. Since some of the low frequency measurements from the ascending

Table 4.5. Thresholds of CLW amount (kg m^{-2}) and observation error σ_o (K) for AMSR-E channels.

Frequency (GHz)	10.65		18.7		23.8		36.5	
polarization	V	H	V	H	V	H	V	H
σ_o (K)	0.73	0.95	0.92	1.20	1.17	1.84	0.84	1.60
CLW (kg m^{-2})	0.35		0.3		0.25		0.1	

orbit in the Southern Hemisphere are affected by a sun glint effect, these data are also excluded based on a sun glint angle ($\leq 25^\circ$) in the quality control procedure. The same radiance bias correction scheme is used with the current GSI scheme (Okamoto and Derber, 2006). CLW retrieval is used as one of the predictors in the bias correction scheme to partially correct for residual cloud effects.

Figure 4.6 shows histograms of AMSR-E brightness temperature differences ($TB_{\text{cal}} - TB_{\text{obs}}$). Cloud-affected data are excluded, and the biases seem to be properly corrected. The frequency distributions are close to the normal distribution. Figures 4.7 and 4.8 show the horizontal distribution of brightness temperature differences ($TB_{\text{cal}} - TB_{\text{obs}}$) for the AMSR-E channels used. The left-hand side panels show figures prior to the bias correction and the right-hand side panels after bias correction. For the 36.5-GHz channels, a negative bias remains in the high-latitude areas after bias correction and may indicate either real information or inadequacies in the bias correction for these channels. The bias correction has two parts - one is scan dependent and the other is airmass dependent. The former is not as dependent on geophysical location for these channels. The latter is estimated from five predictors using a linear regression. The predictors, set to be constant, are scan angle (0 for AMSR-E), cloud liquid water, integrated weighted lapse rate, and its square. The coefficients are optimized for each channel in the analysis and then used for the next analysis in the assimilation cycle. The same coefficients are used globally. Therefore, the remaining bias in the 36.5-GHz channels may represent insufficient background accuracy in the lower tropospheric temperature and/or surface wind speed in the high latitudes. As wind speed is not included as a predictor in this scheme, using a different predictor (wind speed and/or sea surface temperature) might show better performance. Improving the radiance bias correction scheme is big issue. But, in general, the results suggest that the data selection, quality control procedures, and bias correction are working properly.

4.5.3. Experimental Results

IMPACTS ON ANALYSIS

Because the AMSR-E measurements use microwave window channels, the information should be concentrated in the surface wind speed, temperature, and moisture in the lower troposphere. Figures 4.9(a),(b) shows the zonal mean distribution of the root-mean-square (RMS) of the wind speed analysis increment at the lowest sigma level (0.9973). Figures 4.9(c),(d) shows

4.5. ASSIMILATION EXPERIMENTS

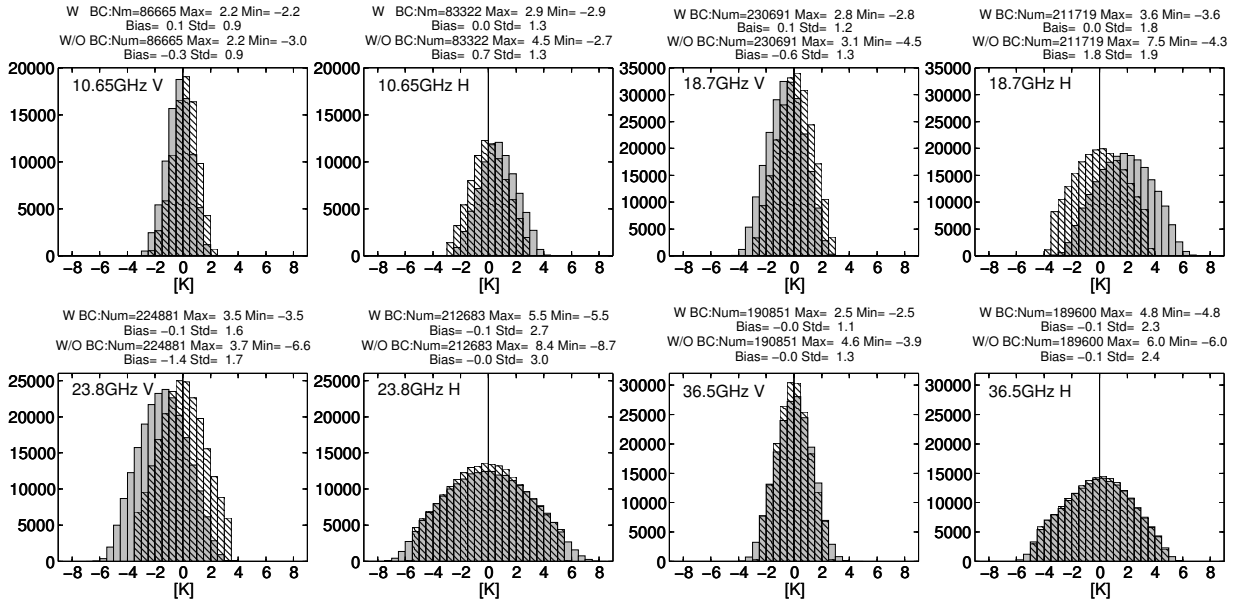


Figure 4.6. The histograms of AMSR-E brightness temperature differences between the calculated brightness temperature (TB_{cal}) and observed brightness temperature (TB_{obs}). The histograms are for AMSR-E radiance data that passed the quality control in Test2. The statistics were calculated for the period 12 Aug – 11 Sep 2005. The gray histograms are for the data without bias correction, and hatched histograms are for data with bias correction. The statistics (data number, maximum, minimum, bias, and standard deviation) are shown.

the RMS difference from the Cntl. The reduction in the lowest level wind speed increments indicates smaller differences from the 6-h forecast and, thus, an improvement in the first-guess wind speed. The improvement is located in the high latitudes of the Southern Hemisphere for the Test2 case, with a smaller impact in Test1 than Test2.

Changes in temperature and moisture in the lower troposphere of the analysis were also found. Figure 4.10 shows the averaged 850-hPa temperature difference from the Cntl run during the experiment period. Figure 4.11 shows the averaged specific humidity difference from the Cntl run. In Test1, there were no significant differences in the averaged analysis fields. However, an increase in temperature (about 0.2 K) in the high latitudes (Figure 4.10(b)) and a decrease in the humidity (about 0.1 g kg⁻¹ over the oceans (Figure 4.11(b)) were found in Test2. The area of decreased humidity is limited to the ocean; in particular, to the dry area outside of the inter-tropical convergence zone (ITCZ). This is a reasonable result because the clear or thin cloud radiances were assimilated in these experiments. Generally, impacts on the analysis from AMSR-E radiances were found over the oceans in data-sparse areas. Therefore, it was difficult to capture these impacts from fits to radiosonde observations (RAOBs) or in comparisons with other conventional observations. There was no significant differences in the mean 6-h rain rate for either experiment, but a slight reduction in the first-guess mean total precipitable water bias was found in the Southern Hemisphere.

CHAPTER 4. IMPACT STUDY OF AMSR-E RADIANCES IN THE NCEP GLOBAL DATA ASSIMILATION SYSTEM

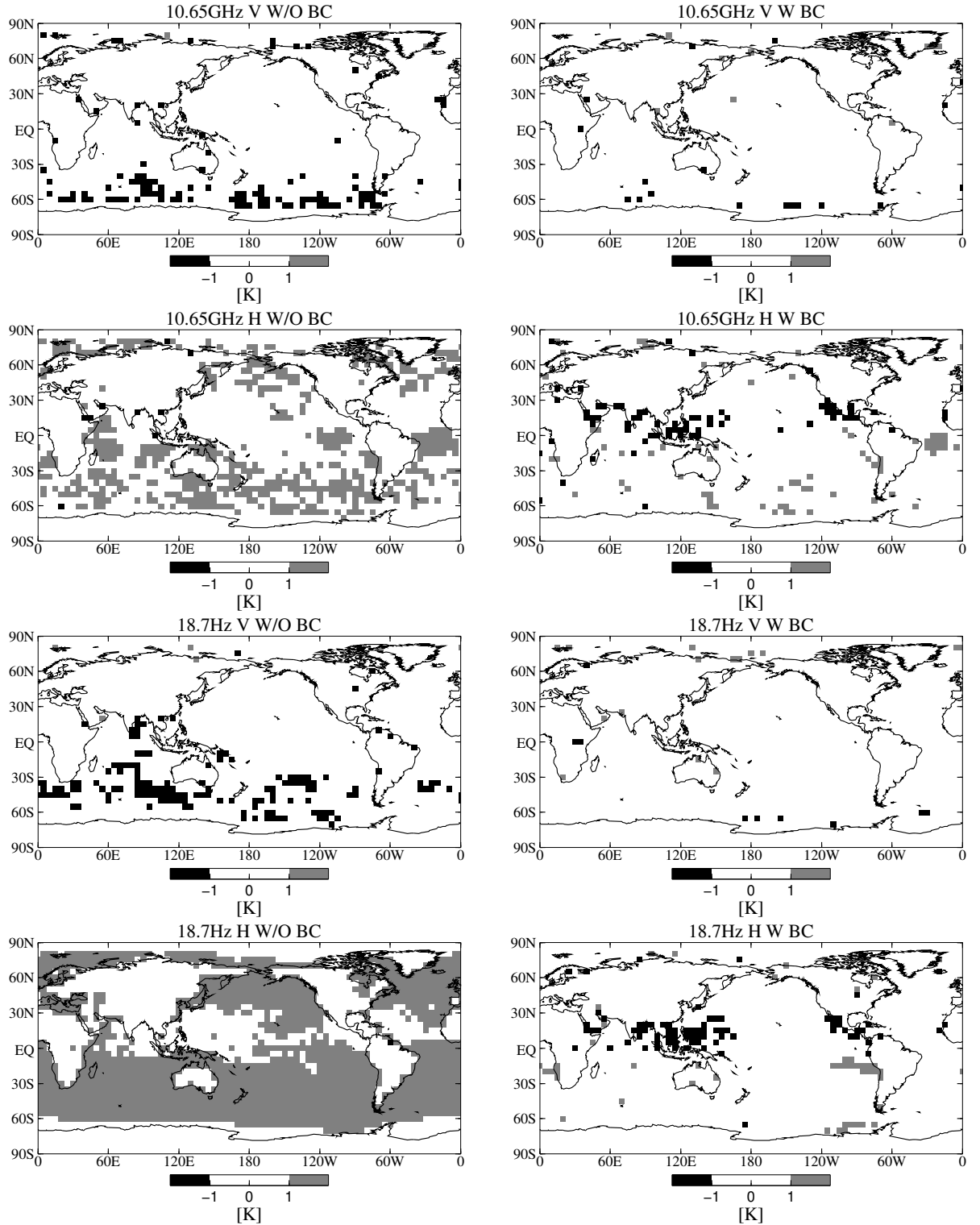


Figure 4.7. Horizontal distribution of the AMSR-E brightness temperature differences ($TB_{cal} - TB_{obs}$) from Test2 (left) without bias correction and (right) with bias correction for both polarizations at 10.65 and 18.7 GHz. The period is for 12 Aug – 11 Sep 2005, and the grid size is $5^\circ \times 5^\circ$.

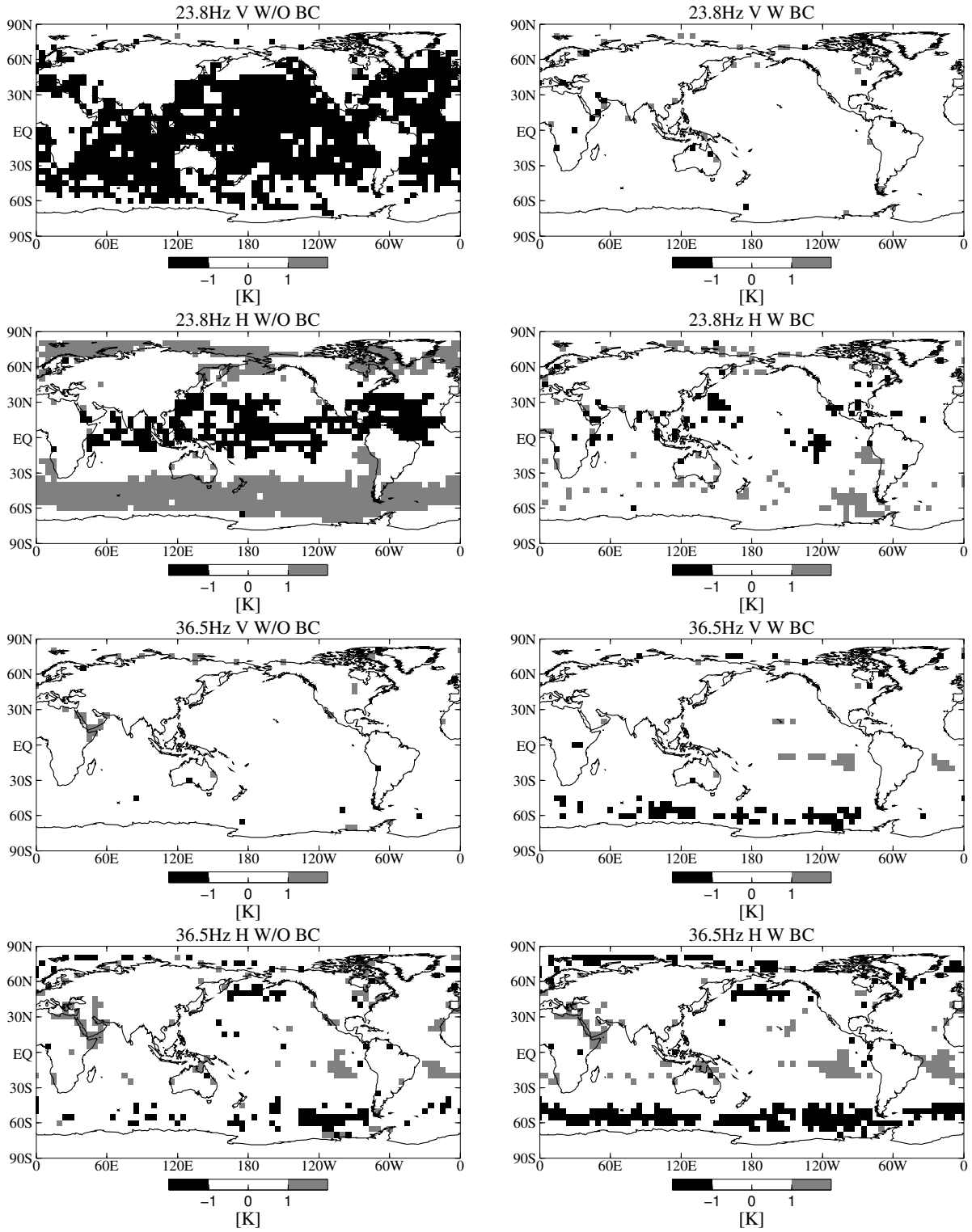


Figure 4.8. As in Figure 4.7, but at 23.8 and 36.5 GHz.

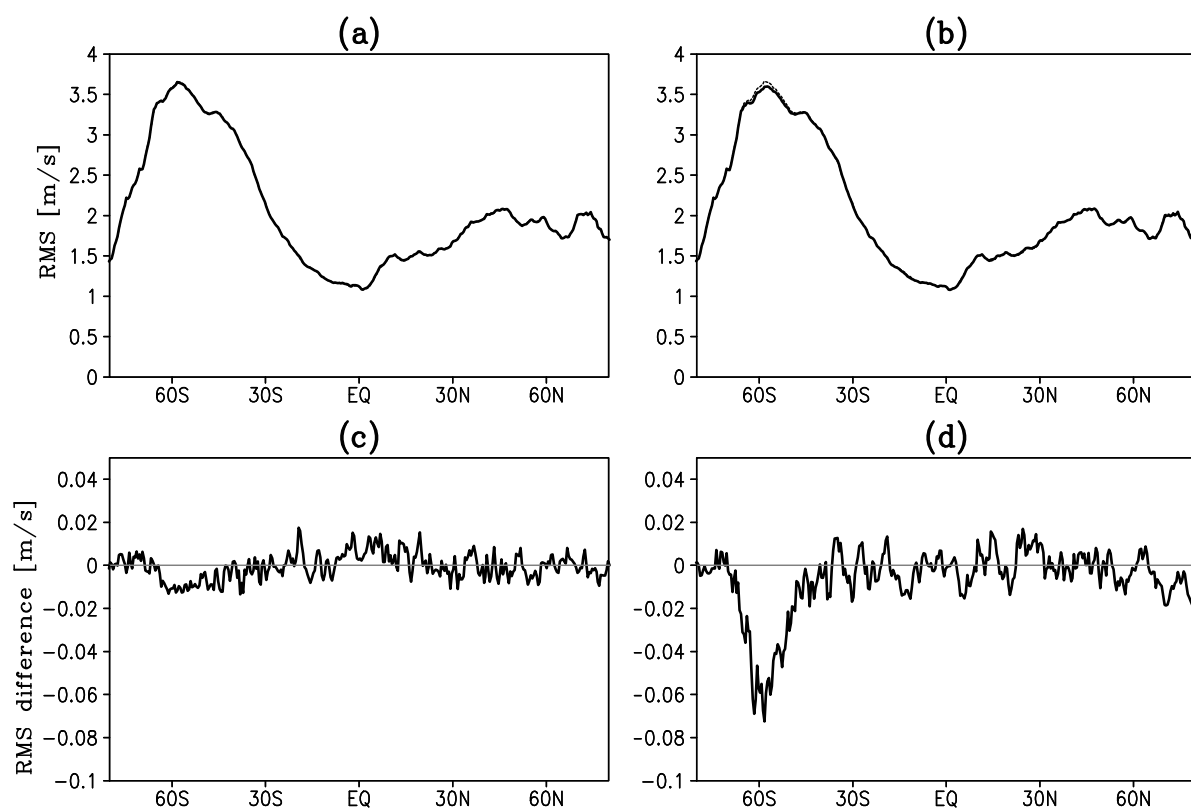


Figure 4.9. The zonal mean distribution of the RMS of the wind speed analysis increment at the lowest sigma level (0.9973): (a) Test1 and (b) Test2. The solid lines in (a) and (b) are Test1 (or Test2), and the broken lines are for the Cntl run. The difference from the Cntl for (c) Test1 and (d) Test2. The statistics are computed for the period of 12 Aug – 11 Sep 2005.

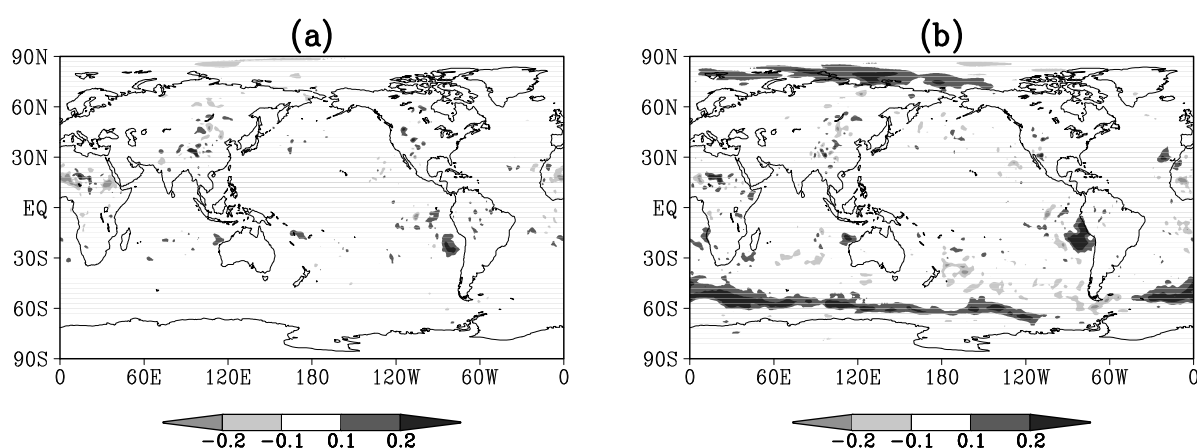


Figure 4.10. Averaged 850-hPa temperature difference (K) between the Test1 (or Test2) and Cntl runs: (a) Test1 and (b) Test2. The statistical period is 12 Aug – 11 Sep 2005.

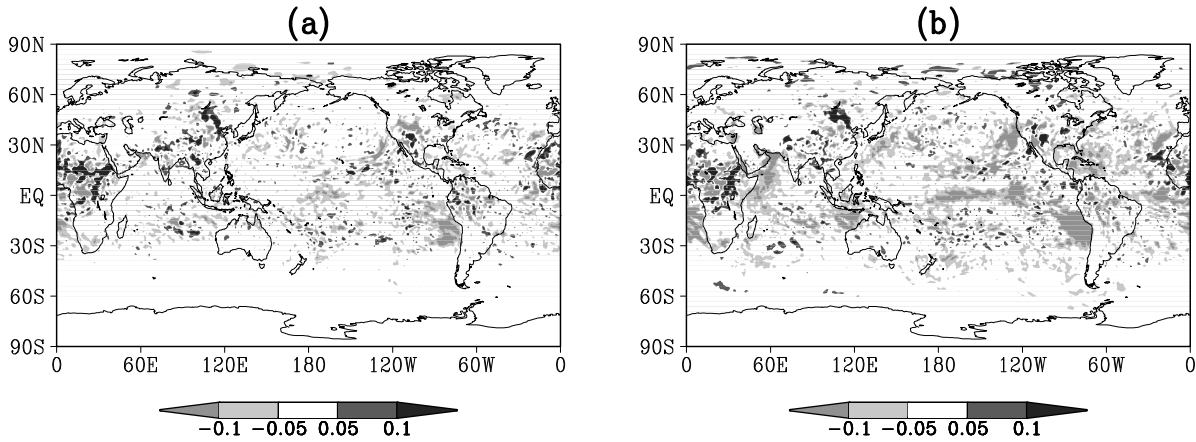


Figure 4.11. As in Figure 4.10, but for specific humidity (g kg^{-1}).

IMPACTS ON FORECAST

Although the impacts of the assimilation of AMSR-E radiances on analyses were primarily over limited areas of the Southern Hemisphere and oceanic regions, the forecast impacts are found over larger regions. Figure 4.12 shows the anomaly correlation coefficients in the extratropics (latitudes 20° - 80° N/S) for 1000- and 500- hPa geopotential heights. Impacts in the Northern Hemisphere were almost neutral while significant improvements (about 1% for the 5-day forecasts) were found in the Southern Hemisphere in both experiments. Ratios of cases where the anomaly correlation coefficients are larger in Test2 than the Cntl over the total number of cases (31 for the initial time and 24 for the 168-h forecast) are also shown in Figure 4.12 by histograms. The ratios for the Southern Hemisphere exceed 50% for all forecast hours.

As for the verification of forecast wind fields, the fits to RAOB for the 24- and 48-h wind vector forecasts were calculated. In the Northern Hemisphere and tropics, there was no significant difference in either experiment. However, slight improvements were found in the lower troposphere and around the 300-hPa height in the Southern Hemisphere (Figure 4.13). For other geophysical parameters, such as temperature, moisture, and geopotential height, similar improvements were confirmed in the Southern Hemisphere. Figures 4.14(a),(b) show zonal mean RMSE of 500-hPa geopotential height for 5-day forecasts. The errors were calculated against their own analysis. In Figures 4.14(c),(d), their differences from the Cntl were shown with negative values indicating a forecast improvement. Improvements in the extratropics were clearly found in both experiments. Figures 4.15(a),(b) show zonal mean RMSE of the 5-day temperature forecast from 1000 to 100 hPa. Figures 4.15(c),(d) show their RMSE difference from the Cntl with the negative values indicating a forecast improvement. The improvements in Test2 were generally larger than those in Test1.

Consistent impacts on the analysis and forecast in another experiment period (1 – 21 December 2005) were obtained. During the former experiment period (12 August – 11 September 2005), a hurricane (Katrina) existed in the northern Gulf of Mexico. In 2005, Katrina was an

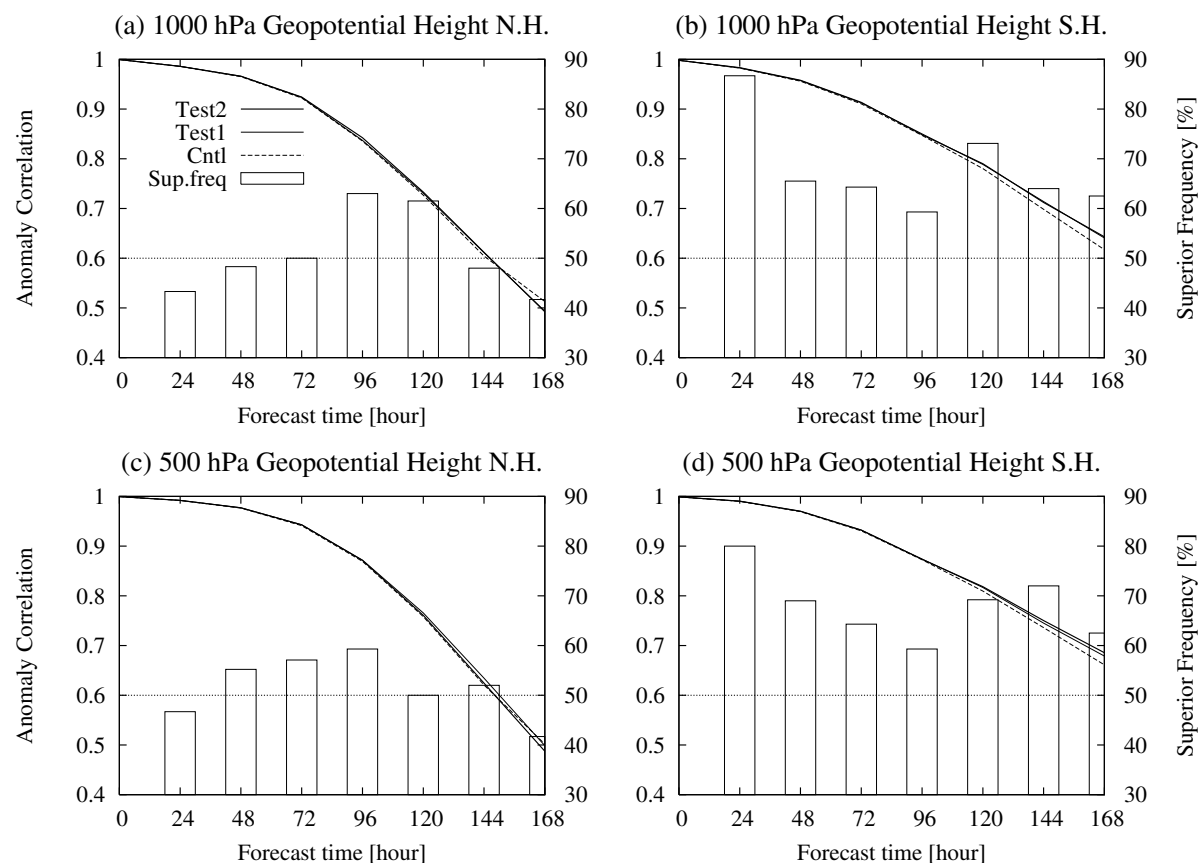


Figure 4.12. Averaged anomaly correlation coefficient at 1000 hPa in the (a) Northern Hemisphere and (b) Southern Hemisphere and at 500 hPa in the (c) Northern Hemisphere and (d) Southern Hemisphere. The statistics are computed for 12 Aug – 11 Sep 2005, with 31 cases at the initial time and 24 cases for the 168-h forecast. Histograms represent the ratio of number of Test2 cases superior to the Cntl, with the scale given on the right axis.

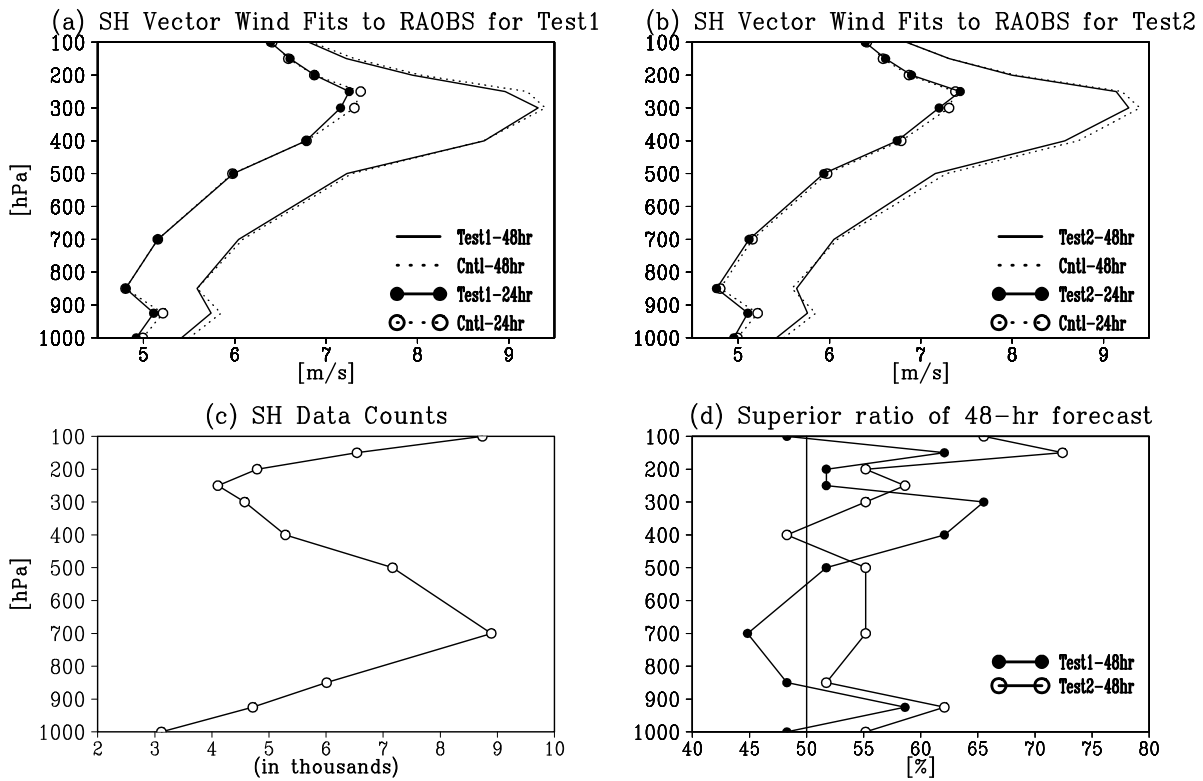


Figure 4.13. Vertical profiles of the RMSE of the 24- and 48-h forecasts for vector wind (m s^{-1}) verified against radiosonde observations in the Southern Hemisphere. Vertical axis units: hPa. The statistics are computed for 0000 UTC 14 Aug – 0000 UTC 11 Sep 2005: (a) Test1 and (b) Test2. The Cntl run statistics are shown by dotted lines, and those from Test1 (or Test2) are shown by solid lines. The RMSEs of the 24-h forecast are shown with a circle, and those of the 48-h forecast are shown by the lines without a circle. (c) The RAOB data counts and (d) the ratio of the number of test cases superior to the Cntl for the 48-h forecast with a black (or white) circle for Test1 (or Test2).

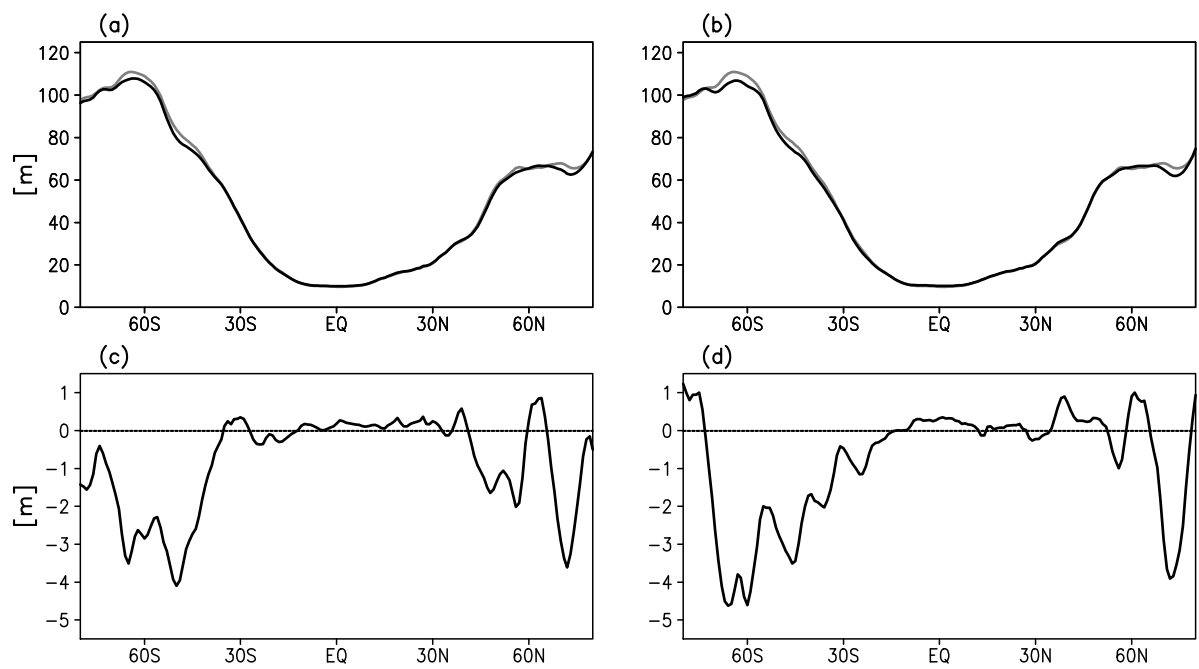


Figure 4.14. Zonal mean RMSE of the 500-hPa geopotential height for the 5-day forecast for (a) Test1 and (b) Test2. The gray line is the Cntl, and the black line is Test1 (or Test2). The errors were calculated against their own analysis. Also shown are the RMSE differences from the Cntl for (c) Test1 and (d) Test2. The period for these statistics is 17 Aug – 11 Sep 2005.

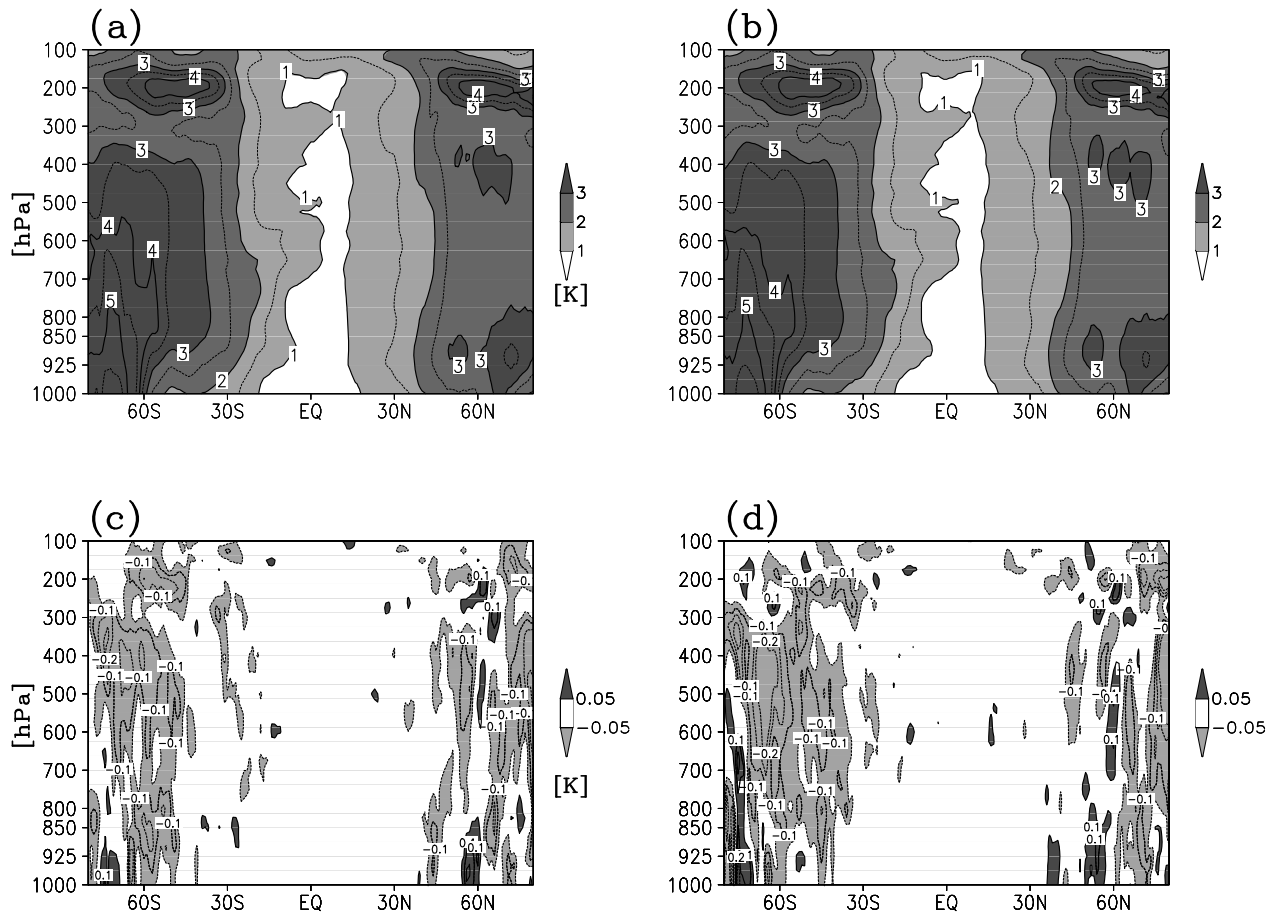


Figure 4.15. Zonal mean RMSE of the 5-day temperature forecast from 1000 to 100 hPa for (a) Test1 and (b) Test2 and the difference in RMSE from the Cntl for (c) Test1 and (d) Test2. The period is 17 Aug – 11 Sep 2005.

extraordinarily strong hurricane (Knabb et al., 2005) and caused serious damage in the United States. As a case study, the track prediction from each experiment was examined. Figure 4.16 shows the comparison of the hurricane track predictions (0000 UTC initial forecasts). Katrina reached the hurricane stage by 0000 UTC 26 August and continued as a hurricane through 1800 UTC 29 August. The forecasts from 0000 UTC 25 August initial field have large errors for Cntl, Test1, and Test2. The errors were not improved when AMSR-E radiances were assimilated in the experiments. However, differences in the track prediction were found in the 26 and 27 August cases. In the 26 August case, an improvement was found in Test2 while Test1 degraded the forecast relative to the Cntl. In the 27 August case, both experiments degraded the forecast accuracy but Test2 showed a slightly better result than Test1. It is clear that there are an insufficient number of cases to determine any clear signal concerning hurricane track forecasts from these results.

4.6. Summary

In this study, a new microwave ocean emissivity model was developed for use in the assimilation of AMSR-E low frequency channels. The new microwave ocean emissivity model was a two-scale model empirically tuned to satellite measurements. Comparisons of the calculated brightness temperatures with observations indicated that the new emissivity model performs better at low frequencies. A clear reduction of the wind-dependent bias was seen in the AMSR-E 10.65 GHz horizontally polarized channel. The sensitivity study showed that FASTEM-1 and the new emissivity model had a similar sensitivity to the sea surface temperature in the 6.925 – 89-GHz microwave frequencies. However, the new model had a much weaker sensitivity to surface wind speeds than FASTEM-1. A quality control procedure for AMSR-E radiances was developed for the data assimilation. To exclude cloud- and rain contaminated data, it was necessary to consider the size of the FOV for low frequency channels because they have a much larger FOV. The 6.925-GHz channels were not used because their FOV (43.2 km $\times$ 75.4 km) was larger than the resolution of the analysis (about 50 km).

In the assimilation experiments, the impact of AMSR-E radiances on the surface wind speed analysis appeared to be limited to the Southern Hemisphere high latitudes. Because the operational dataset already included many surface wind-related data [i.e., retrieved SSM/I wind speed data (Yu et al., 1997) and QuikSCAT wind data (Yu, 2003)], the ability to improve the near surface wind analysis over the ocean could be limited. The new emissivity model resulted in an increase in temperature (about 0.2 K) at 850 hPa in the high latitudes. AMSR-E radiances produced a decrease in humidity with the new emissivity model giving a larger decrease than that from FASTEM-1. The humidity decrease was limited to the low CLW and low humidity area outside of the ITCZ and made no difference in mean 6-h rainfall in the assimilation cycle. This result was reasonable because only clear and thin-cloud AMSR-E radiance data were assimilated in the experiments. Although the impact from limited usage of AMSR-E radiance data was small, including the cloudy radiances (through the use of clouds in the radiative transfer) could bring about larger impacts in the tropics.

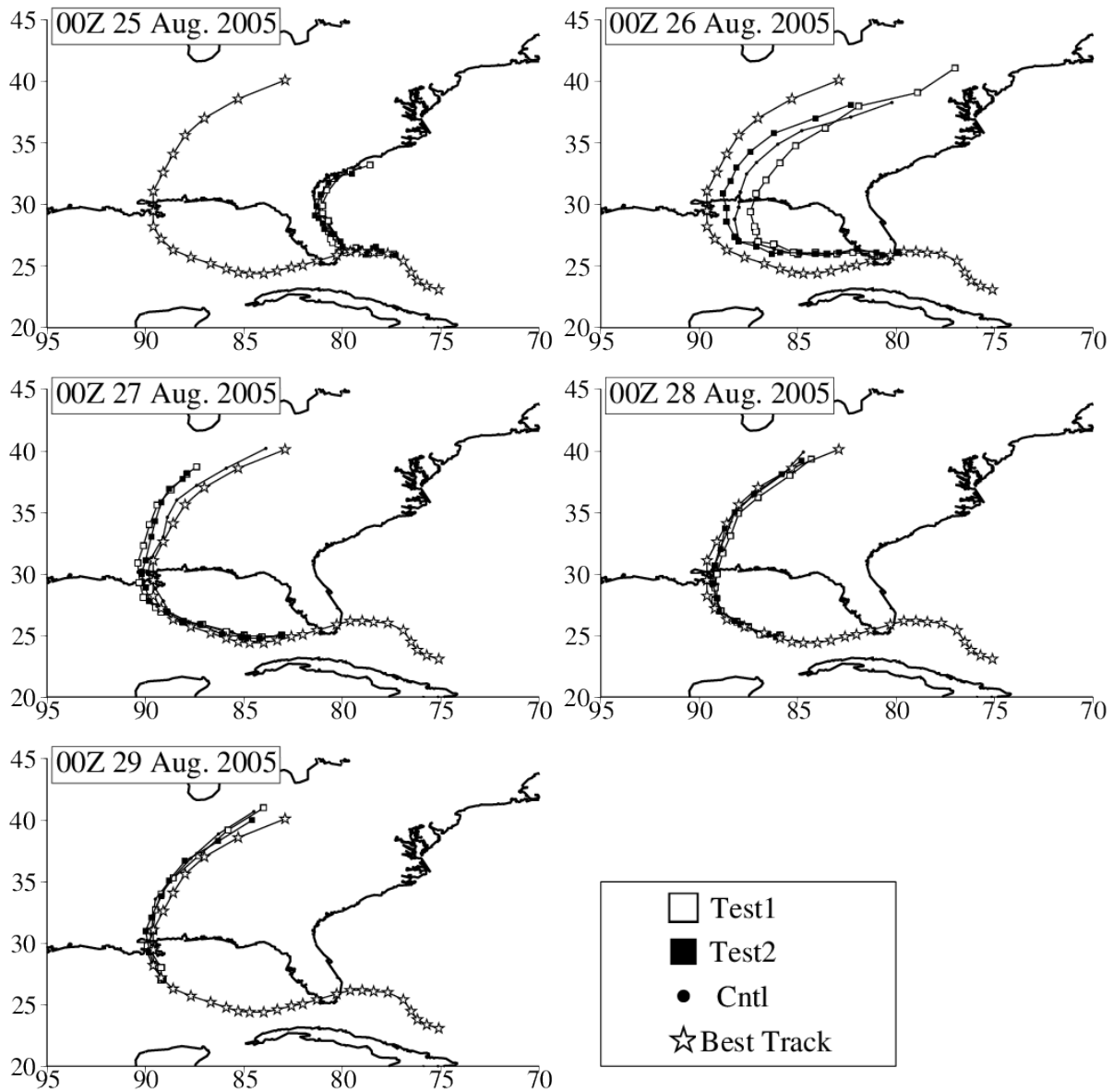


Figure 4.16. Comparison of hurricane track predictions for Katrina in 2005. The samples are from the 0000 UTC initial forecast for 25 – 29 Aug 2005. The symbols show the center of the hurricane every 6 h.

The forecast anomaly correlation scores of geopotential height at 500 and 1000 hPa were improved in the Southern Hemisphere in both experiments (Test1 and Test2). These results indicated that AMSR-E radiances bring a positive impact to the Southern Hemisphere no matter which emissivity model was used. Neutral impacts in the tropics and the Northern Hemisphere (slightly positive) were found. Because most of the impacts on the analysis of surface wind speed and temperature were limited to the high latitudes of the Southern Hemisphere, the impacts on mid-latitude forecasts appeared at a later stage of the forecast range. The decreases of RMSE in the 500-hPa geopotential height and temperature forecasts from 1000 to 100 hPa were also confirmed. A larger improvement was obtained when the new emissivity model was used. These results suggested that the analysis of surface wind speed and temperature in the high latitudes is an important factor in improving the forecast score. A consistent impact on the analysis and forecast in another experiment period (1 – 21 December 2005) was obtained. In the case study of Hurricane Katrina in 2005, no significant improvement was found, while the use of FASTEM-1 for AMSR-E radiances actually degraded the track prediction. The assimilation of AMSR-E radiance data with the new emissivity model improved the track forecast for Hurricane Katrina in the 26 August 2005 case.

In summary, AMSR-E radiance assimilation using the new emissivity model impacted both analyses and forecasts. These results suggest that the use of AMSR-E radiances will bring some improvement to the NCEP operational NWP system, and the new emissivity model can effectively extract information about the ocean surface from AMSR-E low frequency channels.

5. Use of the Ocean Surface Wind Direction Signal in Microwave Radiance Assimilation

5.1. Introduction

Microwave radiance data measured from satellites are a crucial data source in data assimilation for NWP. Radiance data are assimilated as brightness temperatures by means of radiative transfer calculations. Oceanic microwave radiance data contain various kinds of geophysical information: water vapor, atmospheric hydrometeors, and ocean surface conditions. The sensitivity needs to be included in the radiative transfer calculations to make consistent changes in the initial state.

Ocean surface properties can be represented by a small number of parameters because the ocean surface is more homogeneous than the land surface. For calm oceans, ocean surface emissivity can be accurately computed by using the Fresnel equation and assuming a specular surface. The emissivity is expressed as a function of permittivity, sea-surface temperature, and incidence angle. In practice, the ocean surface is rough. The primary cause of surface roughness is wind. The ocean surface roughness increases the emissivity. Accurate modeling of the ocean surface emissivity is necessary in physically based remote sensing both for geophysical parameter retrievals and in data assimilation.

In the previous chapter, biases related to surface wind speed in calculated microwave radiances were investigated in the emissivity modeling. In reality, observed oceanic microwave radiance contains not only the surface wind speed but also the surface wind direction signal. In the low wind speed range ($< 7 \text{ m s}^{-1}$), the azimuthal variation is minor. However, in high wind speed conditions, the effects cannot be neglected because the amplitude of the radiance variation reaches approximately 2 K. High wind speed conditions occur with high impact weather. Accurate representation of this meteorological phenomenon in the emissivity modeling can directly contribute to extracting ocean surface information from the radiance observations through data assimilation. The result is better NWP forecasts.

However, the azimuthal model functions in FASTEM-3, -4, and -5 have not been used for microwave imagers at operational NWP centers because sensor azimuth angle information is not always available in real-time radiance data and because of insufficient modeling of the azimuthal variation in the emissivity model. The FASTEM-5 azimuthal model function is employed for microwave sounding instruments (e.g., the Advanced Microwave Sounding

Unit-A (AMSU-A), Microwave Humidity Sounder (MHS)) in the ECMWF system. However, because surface-sensitive window channels in the microwave sounding instruments (i.e., AMSU-A channels 1, 2, 3, and 4 and MHS channels 1 and 2) are not actively assimilated (they are used only for quality control of the lower tropospheric channels), it is thought that the azimuthal variation of the surface emissivity in microwave sounding data has a minor effect on data assimilation.

Furthermore, other biases in simulated radiance have been thought to be much larger than that from the surface wind direction signal. Therefore, the importance of the azimuthal variation in the microwave imager measurements was thought to be negligible (Bormann et al., 2011) and has been overlooked by the radiance assimilation community. No investigation has yet focused on the effect of azimuthal variation on microwave radiance assimilation.

The goal of this study is to investigate the impact of the wind direction signal on microwave radiance assimilation. To achieve this, the missing sensor azimuth angles in real-time data are calculated based on satellite sensor locations and scan geometry for the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and Special Sensor Microwave Imager/Sounder (SSMIS). A new RWD model function was developed to express the azimuthal variation for microwave radiance assimilation. The RWD model function is compared with the present model functions in FASTEM-5 and FASTEM-3, and a data assimilation experiment using the RWD model function is performed to examine its impact.

In section 5.2, the microwave ocean emissivity models, the derivation of the RWD model function, and the results of their comparison are described. In section 5.3, the impact study and the experimental results are presented. Section 5.4 is the summary. The definition of the azimuth angle used in this study and relevant angle information are described in Appendix B.

5.2. Modeling of Microwave Ocean Surface Emissivity

Because observed azimuthal variation of the radiance showed harmonic cosine function's variation in terms of RWD space (Yueh et al., 1995; Wentz, 1992), RWD model to be developed in this study uses a second-order harmonic expansion as shown in Eq. (5.1). Coefficients in Eq. (5.1) have wind speed dependence. They are modeled with Eqs (5.2) and (5.3) for vertically polarized channels and Eqs (5.4) and (5.5) for horizontally polarized channels. The wind speed dependencies of the coefficients are different between the vertical and horizontal channels.

For the vertically polarized channels, the first harmonic term is dominant and its amplitude increases with surface wind speed. This characteristic can be modeled with the third-order polynomial function in Eq. (5.2). For low wind-speed conditions ($< 7 \text{ m s}^{-1}$), the magnitude of the coefficients are small. However, they grow rapidly between 7 and 16 m s^{-1} . At high wind speeds ($> 16 \text{ m s}^{-1}$), the 19, 37 and 89 GHz vertically polarized channels wind-speed sensitivity saturates although no saturation is seen in horizontally polarized low-frequency channels. This characteristic can be modeled with an exponential term in Eq. (5.2). The variation of the second-term coefficients is relatively small compared to the first term. A

linear function is therefore sufficient for the wind speed range from 0 to 18 m s⁻¹.

For the horizontally polarized channels, the second term in Eq. (5.1) is dominant. The variation of the second term in terms of wind speed is modeled with a third polynomial function and the exponential term as was the case for the first term for the vertical channels. The first term can be modeled with a linear function of surface wind speed, as was done for the second term of the vertically polarized channels. A similar approach is adopted in several studies, e.g., Wentz (1992), St. Germain et al. (2002), Meissner and Wentz (2002, 2012).

The RWD model is a function of RWD and surface wind speed and independent from other geophysical parameters (e.g., surface temperature, boundary-layer stability). This approximation is commonly used in other microwave emissivity models. It is possible that the azimuthal variation depends on other parameters, such as significant wave height, ocean current, or boundary-layer stability. But those are beyond the scope of the present study. The emissivity variations are modeled as the following equations:

$$\Delta E_i = E_{i1} \cos \phi_r + E_{i2} \cos 2\phi_r, \quad i = v \text{ or } h. \quad (5.1)$$

$$E_{v1} = a_{v1} \{ \exp(-\alpha_v W^2) - 1 \} (b_{v1} W + c_{v1} W^2 + d_{v1} W^3), \quad (5.2)$$

$$E_{v2} = a_{v2} W, \quad (5.3)$$

$$E_{h1} = a_{h1} W, \quad (5.4)$$

$$E_{h2} = a_{h2} \{ \exp(-\alpha_h W^2) - 1 \} (b_{h1} W + c_{h1} W^2 + d_{h1} W^3), \quad (5.5)$$

where ΔE_i is the azimuthal variation of the microwave ocean emissivity for vertical or horizontal polarization channel. $\phi_r = \phi_w - \phi_s$ is the RWD defined from wind direction ϕ_w and satellite azimuth angle ϕ_s . W is the surface wind speed in m s⁻¹. The coefficients $a_{v1}, b_{v1}, c_{v1}, d_{v1}, \alpha_v, a_{v2}, a_{h1}, a_{h2}, b_{h2}, c_{h2}, d_{h2}$, and α_h were determined from fitting of the model to observed azimuthal variation for each frequency.

5.2.1. Data and Methodology

In order to determine the coefficients of the RWD model function, truth data of microwave radiance and surface wind vector are necessary. In the literature (Wentz, 1992; Meissner and Wentz, 2002, 2012), collocated data between satellite microwave measurements and buoy wind data, or microwave measurements and scatterometer wind data were used. The amount of the collocated data between different platforms is very limited and it is difficult to collect a sufficient data sample covering varied meteorological condition (e.g., from low wind speed to high wind speed) with a short period. In this study, simultaneous measurements of radiance and wind vector by the Advanced Earth Observing Satellite-II (ADEOS-II) are used. The Advanced Microwave Scanning Radiometer (AMSR) and National Aeronautics and Space Administration (NASA) scatterometer SeaWinds were aboard the satellite. The ADEOS-II data are available for seven months (April – October 2003). Temperature and specific humidity profiles and surface temperature from ECMWF reanalysis data (ERA Interim: Dee et al., 2011) were used for simulation of AMSR radiance in radiative transfer calculations. Ebuchi (2006)

Table 5.1. Microwave imager channel frequency.

Band	Notation	Polarization	Sensor (channel number and frequency (GHz))					
			AMSR-E		TMI		SSMIS	
			Ch	Frequency (GHz)	Ch	Frequency (GHz)	Ch	Frequency (GHz)
C	06V	V	1	6.925	–	–	–	–
	06H	H	2	6.925	–	–	–	–
X	10V	V	3	10.65	1	10.65	–	–
	10H	H	4	10.65	2	10.65	–	–
Ku	19V	V	5	18.7	3	19.35	13	19.35
	19H	H	6	18.7	4	19.35	12	19.35
K	23V	V	7	23.8	5	21.3	14	22.235
	23H	H	8	23.8	–	–	–	–
Ka	37V	V	9	36.5	6	37	16	37
	37H	H	10	36.5	7	37	15	37
W	89V	V	11	89.0A	8	85.5	17	91.655
	89H	H	12	89.0A	9	85.5	18	91.655
	–	V	13	89.0B	–	–	–	–
	–	H	14	89.0B	–	–	–	–

reported on the accuracy of ADEOS-II SeaWinds wind data. No systematic biases in the wind speed and direction against buoys were confirmed. Root mean square (RMS) differences of the wind speed and direction were approximately 1 m s^{-1} and 20° in the buoy wind speeds higher than 3 m s^{-1} . Moreover, SeaWinds wind data had less correlation with the thermal condition of the sea surface and the sea state. SeaWinds wind data are used as the inputs of surface wind information in the radiative transfer calculations and the model function developed in this study

The radiative transfer calculations were performed in clear sky conditions with RTTOV-10, but the azimuthal function in FASTEM-5 was turned off to visualize the azimuthal variation in the difference of the observed and simulated AMSR radiances. The AMSR channels cover the microwave frequency range from 6 to 89 GHz. The precise frequencies used in space-based microwave imagers vary from sensor to sensor. Table 5.1 summarizes the frequencies and channel numbers, for available microwave imagers in the data assimilation. Hereafter, notations defined in Table 5.1 are used to specify microwave imager channels. To separate cloud signal and surface signal in the observed AMSR radiances over oceans, cloud-free scenes were selected. An empirical cloud-screening method is used. Two indexes (S_{idx} and P_{idx}) are defined in the following equations:

$$S_{\text{idx}} = (T_{23\text{V}} - T_{19\text{V}}) - C_s \cdot (T_{23\text{V}} - T_{37\text{V}}), \quad (5.6)$$

$$P_{\text{idx}} = (T_{89\text{H}}/T_{89\text{V}}) - C_p \cdot (T_{23\text{V}} - T_{19\text{V}}), \quad (5.7)$$

where $T_{19\text{V}}$, $T_{23\text{V}}$, $T_{37\text{V}}$, $T_{89\text{V}}$ and $T_{89\text{H}}$ are observed AMSR radiances. AMSR data satisfying the following criteria are selected:

$$S_{\text{min}} < S_{\text{idx}} < S_{\text{max}}, \quad (5.8)$$

$$P_{\text{min}} < P_{\text{idx}} < P_{\text{max}}, \quad (5.9)$$

where $C_s = 30.0/40.0$, $C_p = 0.2/30.0$, $S_{\text{min}} = 20.0$, $S_{\text{max}} = 24.5$, $P_{\text{min}} = 0.65$, and $P_{\text{max}} = 0.72$. These thresholds were empirically determined. This empirical cloud detection is based on the

cross-spectral variation of radiances, which is different between clear and cloudy conditions. Figure 5.1 shows examples of the relationship between indices for (a) observed AMSR radiance and (b) simulated clear sky radiance on 1 August 2003. Panel (a) indicates the relationship between $T_{23V} - T_{37V}$ and $T_{23V} - T_{19V}$ for observed radiance. Panel (b) indicates the same relationship but for simulated radiance under clear conditions, and shows the two amounts ($T_{23V} - T_{37V}$ and $T_{23V} - T_{19V}$) have a linear relationship in clear conditions. In other words, the two amounts are proportional in a situation with less cloud and rain (i.e., only water vapor is dominant). Two dashed lines in (a), (b) indicate the threshold ($S_{\min}$ and $S_{\max}$). Furthermore, T_{37V} has a larger cloud liquid sensitivity than T_{19V} . When the observed radiances are largely cloud affected, the data deviate from this relationship. Panels (c) and (d) show relationships of T_{89H}/T_{89V} and $T_{23V} - T_{19V}$ for observed radiance and simulated clear sky radiance, respectively. Most of the simulated data in the clear sky condition lie between the two dashed lines in the diagram. Observed radiances at 89 GHz are much more sensitive than those of 19 or 23 GHz. Therefore, observations falling outside the area between the dashed lines can be thought of as cloud- or rain-affected data. They are removed from the dataset for the coefficient fitting. The parameters C_s , C_p mean gradients and S_{idx} , P_{idx} mean intercepts in the diagrams. This cloud screening is independent of satellite azimuth angle, surface wind speed and direction. Moreover, it is required that the difference of the observed and simulated radiance should be within 5.0 K to remove cloud contaminated data. Sun-glint-affected data in AMSR data were removed in advance. In conversion of the radiance's variation to the emissivity variation, atmospheric transmittance should be taken into account. General microwave radiative transfer can be described by the following equation (Equations (2.18), (6.8) in Janssen (1993)).

$$T_b(\nu, \theta) = T_u(\nu, \theta) + \{\epsilon_s T_s + (1 - \epsilon_s) T_d(\nu, \theta)\} e^{-\tau(0) \sec \theta} \quad (5.10)$$

The left-hand side is observed radiance $T_b(\nu, \theta)$ with frequency ν and incidence angle θ . On the right-hand side, $T_u(\nu, \theta)$ is upwelling radiation, $T_d(\nu, \theta)$ is down-welling radiation, ϵ_s is surface emissivity, T_s is surface temperature, and $e^{-\tau(0) \sec \theta}$ is atmospheric transmittance. Higher-frequency channels have smaller transmittance than those of low-frequency channels in atmospheric profiles under clear sky conditions. Therefore, radiance variations are converted differently depending on mean atmospheric transmittances in the channel's microwave frequency. Conversion coefficients β_i from the radiance to the emissivity are necessary to obtain the final coefficients used in the new model:

$$\Delta T_b = \beta_i \Delta E_i, \quad (5.11)$$

$$\beta_i = T_s e^{-\tau(0) \sec \theta}. \quad (5.12)$$

The coefficients β_i can be thought of as a global mean of surface temperature multiplied by mean atmospheric transmittance for each channel. The β_i were determined by using atmospheric profiles to produce the same amplitude of the azimuth variation between observed and simulated radiances. This is possible because the RWD model function is assumed to be purely dependent on surface wind and there is no dependency on sea-surface temperature or atmospheric properties. Because high-frequency channels, e.g., 89 GHz, are sensitive to

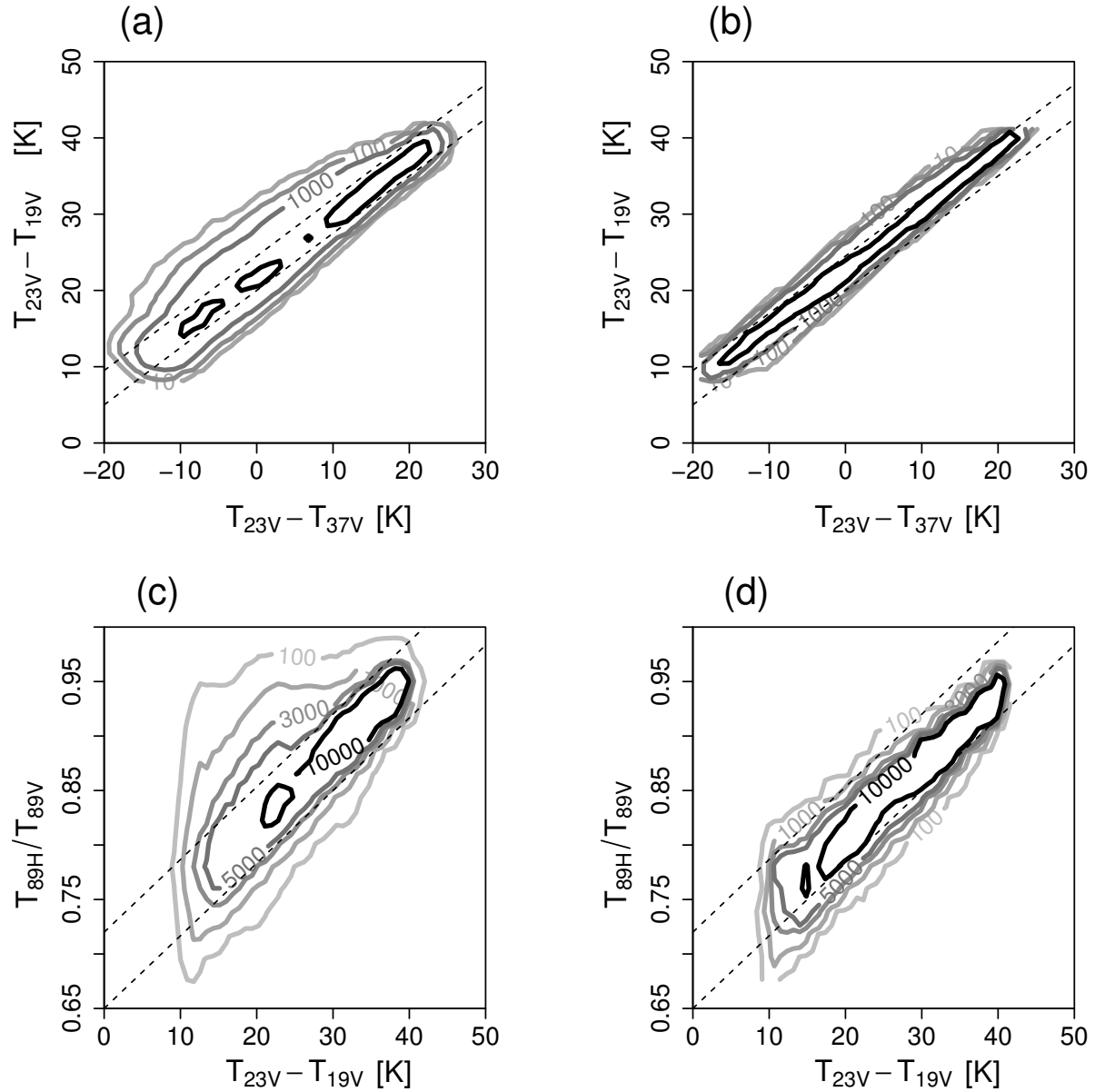


Figure 5.1. Data frequency distributions in cloud-screening parameter space for AMSR data on 1 Aug 2003. (a) $T_{23V} - T_{37V}$ and $T_{23V} - T_{19V}$ for observed radiance, (b) $T_{23V} - T_{37V}$ and $T_{23V} - T_{19V}$ for simulated clear-sky radiance, (c) $T_{23V} - T_{19V}$ and T_{89H}/T_{89V} for observed radiance, (d) $T_{23V} - T_{19V}$ and T_{89H}/T_{89V} for simulated clear-sky radiance. The contour lines indicate the data counts.

clouds in the atmosphere, the 7-month ADEOS-II period was not sufficient to estimate the azimuthal variation in the all wind-speed categories. Therefore, F17 SSMIS data was used instead of AMSR for the 89 GHz channels. The SSMIS has 91 GHz vertically and horizontally polarized channels. The simulated SSMIS data were obtained from microwave all-sky data assimilation system of the ECMWF Integrated Forecasting System (IFS), using cycle 38r2 (Bauer et al., 2013) and run at a horizontal resolution T511 (with a 32 km grid) L137 (with 137 vertical levels) compared to operational resolution in June 2013 of T1279 (with a 16 km grid) L137. No azimuthal model function in the radiative transfer model (RTTOV-10) was used. All the coefficients for 6, 10, 19, 37 and 89 GHz in vertical and horizontal polarization were determined. A linear interpolation in frequency is used to obtain intermediate frequencies (e.g., 23 GHz) needed for other microwave instruments. Thus, the RWD model function is applicable to the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E: Kawanishi et al., 2003), SSMIS and TMI that are actively used in data assimilation.

After subtraction of the mean bias in the difference of observed and simulated AMSR radiance for all wind-speed categories (1 m s^{-1} intervals, from 0 to 18 m s^{-1}), the remaining biases are attributed to the wind directional signal in terms of RWD. Figure 5.2 shows the variations in terms of RWD for a surface wind speed of 12 m s^{-1} . In each panel, the vertical axis indicates the difference between observed and simulated radiance after the bias subtraction. The horizontal axis is RWD defined from SeaWinds wind direction and AMSR azimuth angle. Figure 5.2(a) panels are vertically polarized channels and Figure 5.2(b) panels are horizontally polarized channels. The RWD model function was fitted to the bias between the observed and simulated radiance. The fitting was performed for a wind speed range from 0 to 18 m s^{-1} in 1 m s^{-1} intervals to obtain the wind speed dependency for the coefficients.

A small phase shift between measured RWD signal and fitted model function exists. The phase shift was pronounced in high wind-speed conditions ($> 12 \text{ m s}^{-1}$). At present, the reasons for these discrepancies are unknown. However, the small phase shifts did not affect the estimation of the amplitude of the variation in the wind speed range.

Figure 5.3 shows the coefficients obtained from the fitting for the RWD model function. The coefficients of the first harmonic term are shown in black solid circles. For the second harmonic term they are shown in white squares. Fitted functions are drawn with solid lines. The first harmonic term is dominant for vertical polarization channels and the second harmonic term is dominant for horizontal polarization channels. These results are consistent with other investigations (Meissner and Wentz, 2002, 2012). Large variations of the directional signal in radiance are found. Moreover, wind directional signals for the high-frequency channels (89V and 89H) are found, while the FASTEM-5 azimuth model function in RTTOV has very weak sensitivity for these channels (Figure 5.5). Table 5.2 shows the estimated coefficients for the dual polarization channels of AMSR from 6 to 89 GHz. Tangent linear and adjoint models of the RWD model function were developed for use in variational data assimilation.

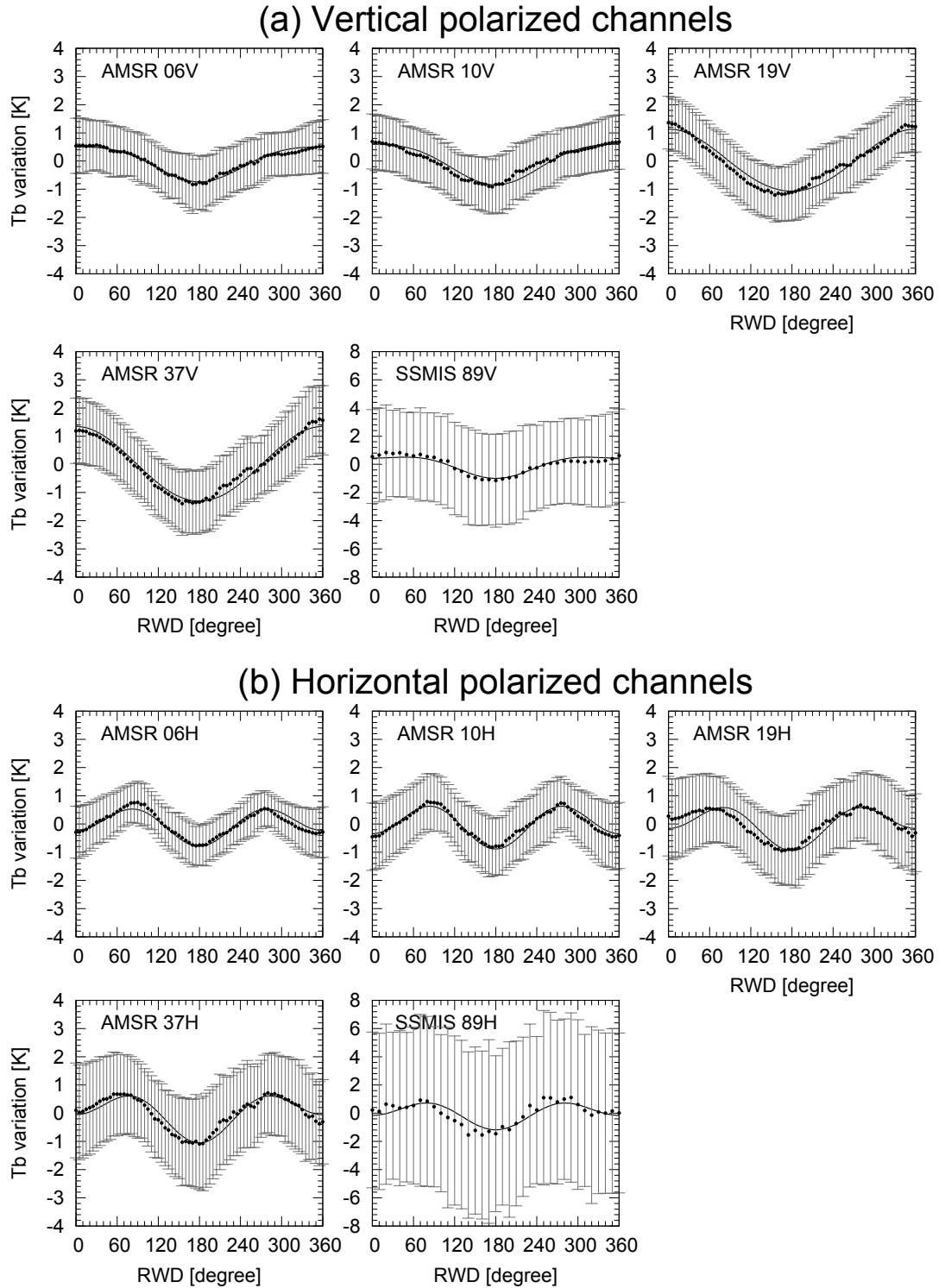


Figure 5.2. Oceanic microwave radiance variation in terms of RWD for surface wind speed 12 m s^{-1} . Panels (a) are vertically polarized channels and panels (b) are for horizontally polarized channels. AMSR radiance and SeaWinds wind vector were used for 6, 10, 19 and 37 GHz. F17 SSMIS radiance and surface wind vector from ECMWF IFS were used (see text section 5.2.1) for 89 GHz. The biases (black filled circles) and standard deviation (error bars) were plotted and fitted model functions were drawn with a black solid line.

5.2. MODELING OF MICROWAVE OCEAN SURFACE EMISSIVITY

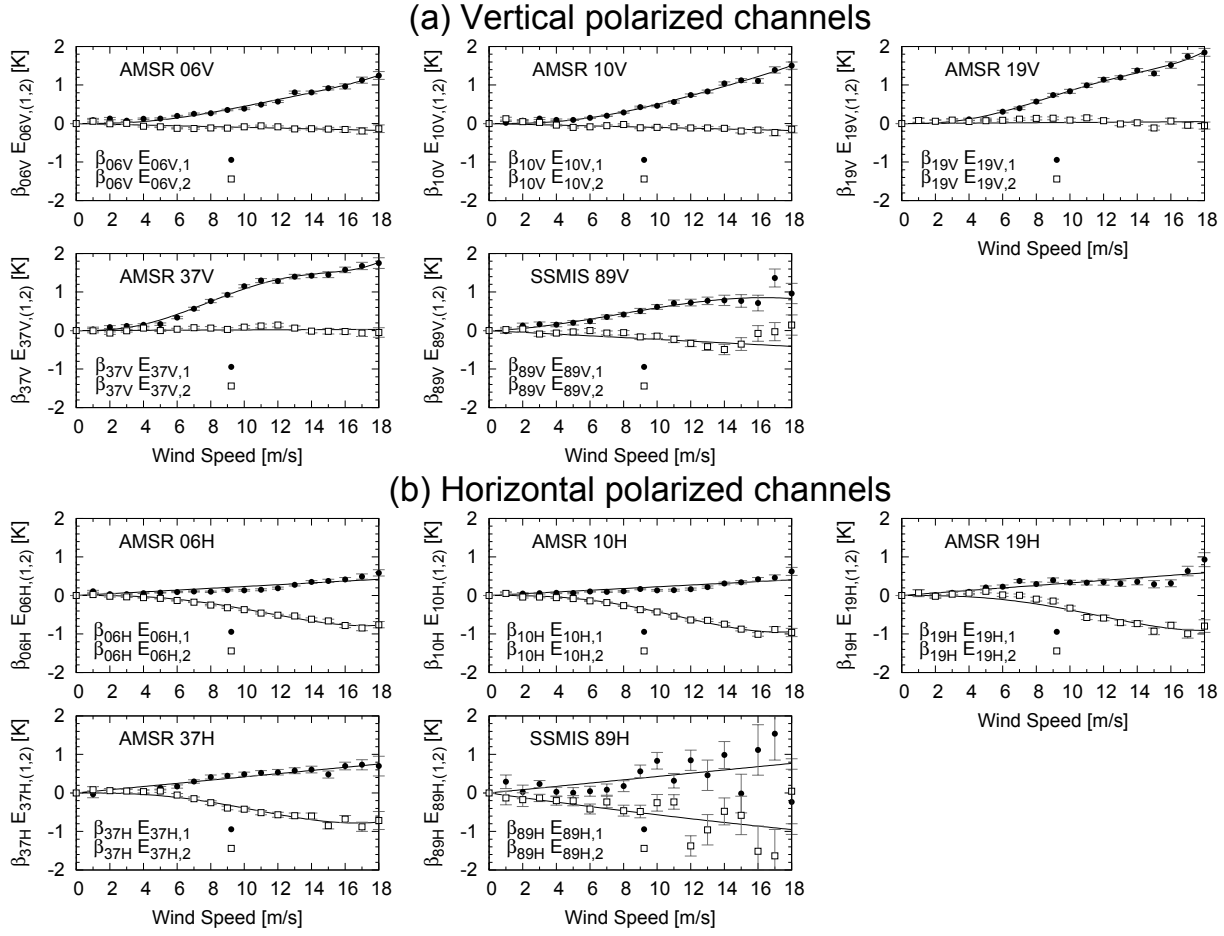


Figure 5.3. The amplitude of the harmonic cosine functions from the azimuthal variation. Black filled circles are the first harmonic term E_{i1} and white squares are the second harmonic term E_{i2} in Eq. (5.1). (a) Fitted functions for vertical channels in terms of wind speed with solid curves (Eqs (5.2) and (5.3)). (b) Same as (a) but for horizontal channels with solid curves (Eqs (5.4) and (5.5)). 06V, 06H, 10V, 10H, 19V, 19H, 37V, 37H are AMSR results and 89V and 89H are F17 SSMIS results.

Table 5.2. Estimated coefficients for the RWD model function.

Channel	a_{v1}	b_{v1}	c_{v1}	d_{v1}	α_v	a_{v2}	β_v
06V	4.394E-02	-1.636E+01	1.348E+00	-3.366E-02	5.828E-06	-3.513E-05	279.72
10V	4.397E-02	-1.639E+01	1.144E+00	-2.487E-02	5.445E-06	-3.604E-05	279.72
19V	5.009E-02	-1.638E+01	1.520E+00	-3.994E-02	1.330E-05	1.113E-05	246.15
37V	5.553E-02	-1.638E+01	1.602E+00	-4.246E-02	1.903E-05	7.524E-06	222.22
89V	-9.131E-05	1.251E+00	6.769E-01	-2.913E-02	1.092E+00	-1.806E-04	126.50
Channel	a_{h1}	a_{h2}	b_{h2}	c_{h2}	d_{h2}	α_h	β_h
06H	8.343E-05	-8.207E-03	-1.040E+01	4.536E-01	0.000E+00	2.589E-05	280.00
10H	8.082E-05	-8.204E-03	-1.040E+01	4.526E-01	0.000E+00	3.121E-05	280.00
19H	1.362E-04	-1.013E-03	-9.235E+00	3.844E-01	0.000E+00	2.891E-04	240.00
37H	1.910E-04	-2.224E-04	-9.232E+00	3.982E-01	0.000E+00	1.673E-03	218.18
89H	3.554E-04	5.226E-04	9.816E-01	-7.783E-03	0.000E+00	2.437E+01	120.00

5.2.2. Comparison with Other RWD Model Functions

The RWD model function performance was compared with other azimuthal model functions. Currently, FASTEM-5 and FASTEM-3 have different azimuthal model functions for the data assimilation. Figure 5.4 indicates calculated emissivity variation from new RWD model function for 6, 10, 19, 37 and 89 GHz at wind speeds of 0, 8, 12, 14 and 18 m s⁻¹. Figures 5.5, 5.6 and 5.7 are as Figure 5.4 but for the FASTEM-5 (in RTTOV and in CRTM) and FASTEM-3 azimuthal model function, respectively. Right vertical axes are scaled in Kelvin in the Figures. The mean biases in each wind speed category were subtracted to show only the azimuthal variation. Comparing Figures 5.4 and 5.5, it is clear that the new RWD model function has a larger amplitude in terms of wind speed than FASTEM-5 in RTTOV. The new RWD model function was derived from real microwave radiance measurements, while FASTEM-5 was based on a theoretical two-scale model simulation results. The amplitudes of FASTEM-3 (Figure 5.7) are similar to the new RWD model. However, FASTEM-5 (Figure 5.5, 5.6) and also FASTEM-3 have sensitivity in the 0 m s⁻¹ wind speed range (less than 0.5 m s⁻¹). This is unphysical behavior. The new RWD model function was designed to have no sensitivity on the azimuthal variation at 0 m s⁻¹ wind speed, because there is less wind direction signal in passive microwave measurements in such low wind-speed situations. The performance of azimuth variations of FASTEM-5 in RTTOV (Figure 5.5) and that in CRTM (Figure 5.6) show different wind speed dependency. It is necessary to compare these azimuth emissivity models to real observations. Figure 5.8 shows comparisons between observed radiance variation from AMSR-E and SSMIS and the model simulations. Figure 5.8(a) shows the AMSR-E 19 GHz vertically polarized channel. The new RWD model and FASTEM-3 are closer to the observations than FASTEM-5. Figure 5.8(b) indicates a case of low wind speed (2 m s⁻¹) for the 19 GHz horizontally polarized channel (AMSR-E 19H). FASTEM-5 shows a large sensitivity to RWD. Figure 5.8(c) indicates a case of high-frequency channel (89V for SSMIS). The new RWD model performances are close to the observed azimuth variation of SSMIS.

Measurements on the incidence angle dependency of the azimuthal variation are very limited, so they were imported from other studies (equation (26) in Meissner and Wentz (2012)) to add incidence angle dependency in the new RWD model. This function is necessary to apply the new RWD model function to cross-track microwave radiometers.

Over wind speed 18 m s⁻¹, ADEOS-II could not provide sufficient data for the fitting. For the high wind-speed cases (> 18 m s⁻¹), the new RWD model assumes that the azimuthal variation has the same amplitude as for a wind speed of 18 m s⁻¹. No extrapolation with wind speed is used. Moreover, the new RWD model does not have the capability to calculate azimuthal variation on the third and fourth Stokes parameters.

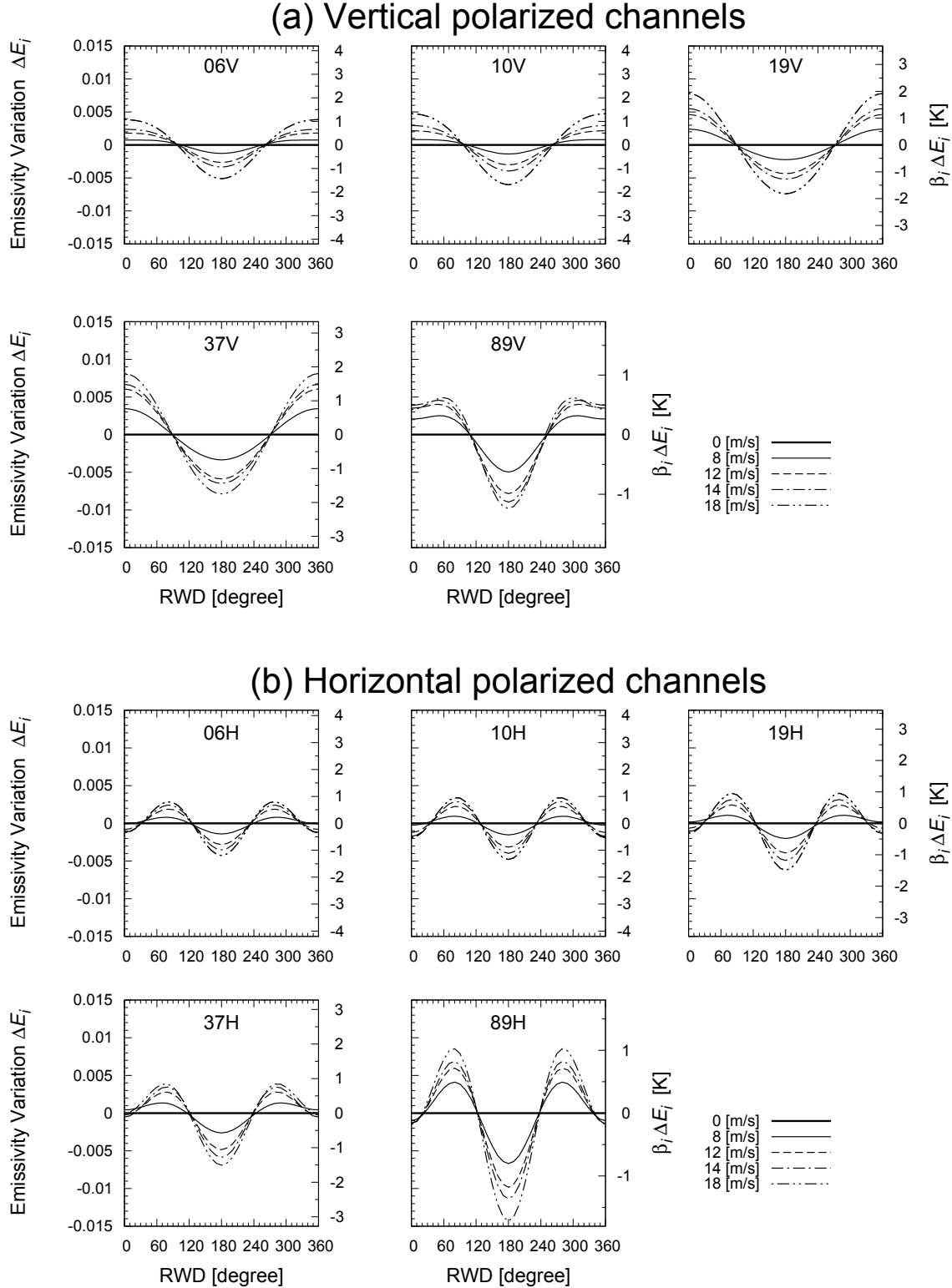


Figure 5.4. The azimuthal variation of the calculated emissivity with the developed RWD model function for 6 – 89 GHz. (a) Vertically polarized channels at 0, 8, 12, 14, 18 m s^{-1} surface wind speed cases. (b) Same as (a) but for horizontally polarized channels. Right vertical axes are scaled in Kelvin by multiplying conversion coefficient β_i .

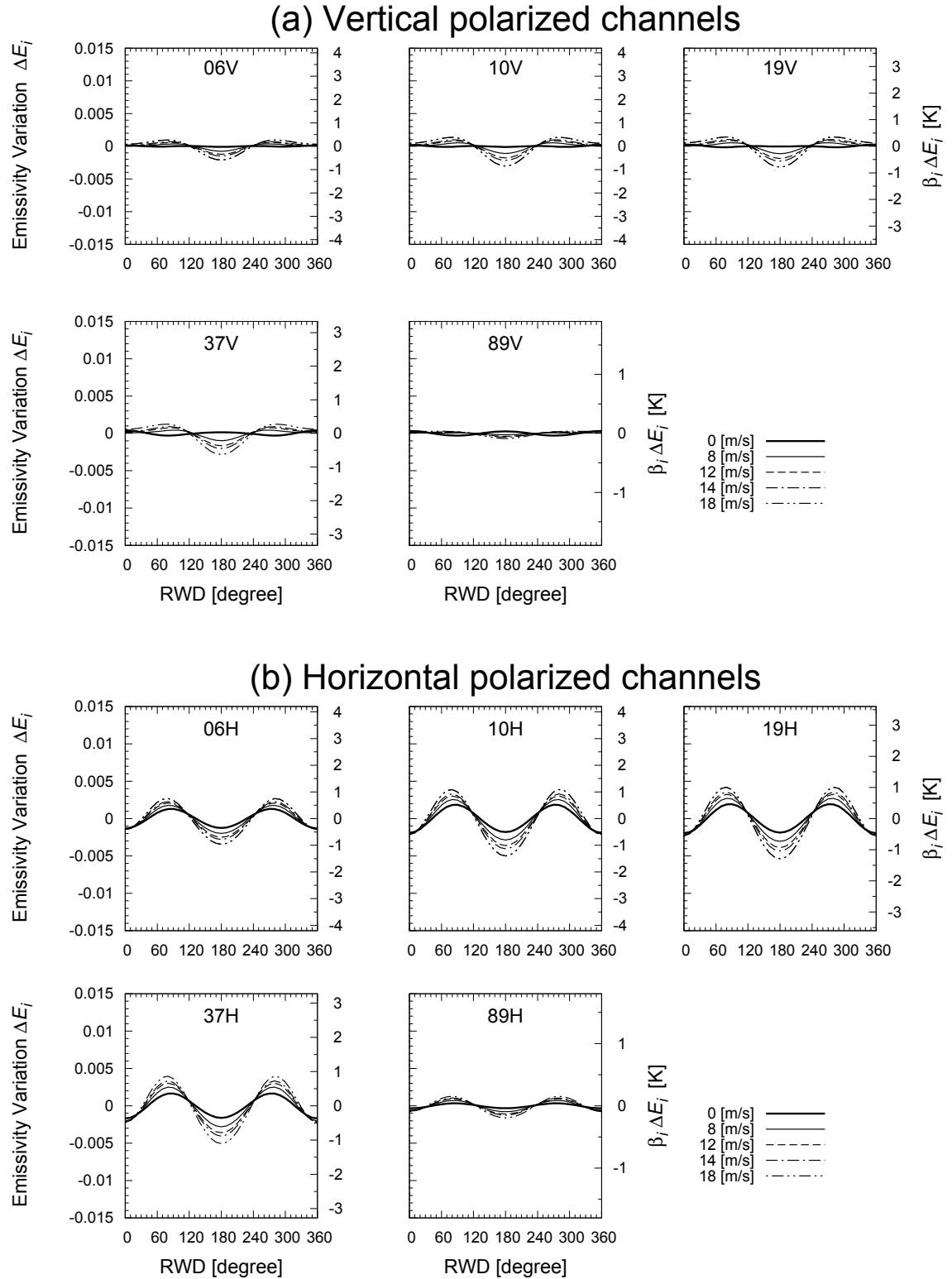


Figure 5.5. Same as Figure 5.4 but for FASTEM-5 azimuthal model function in RTTOV.

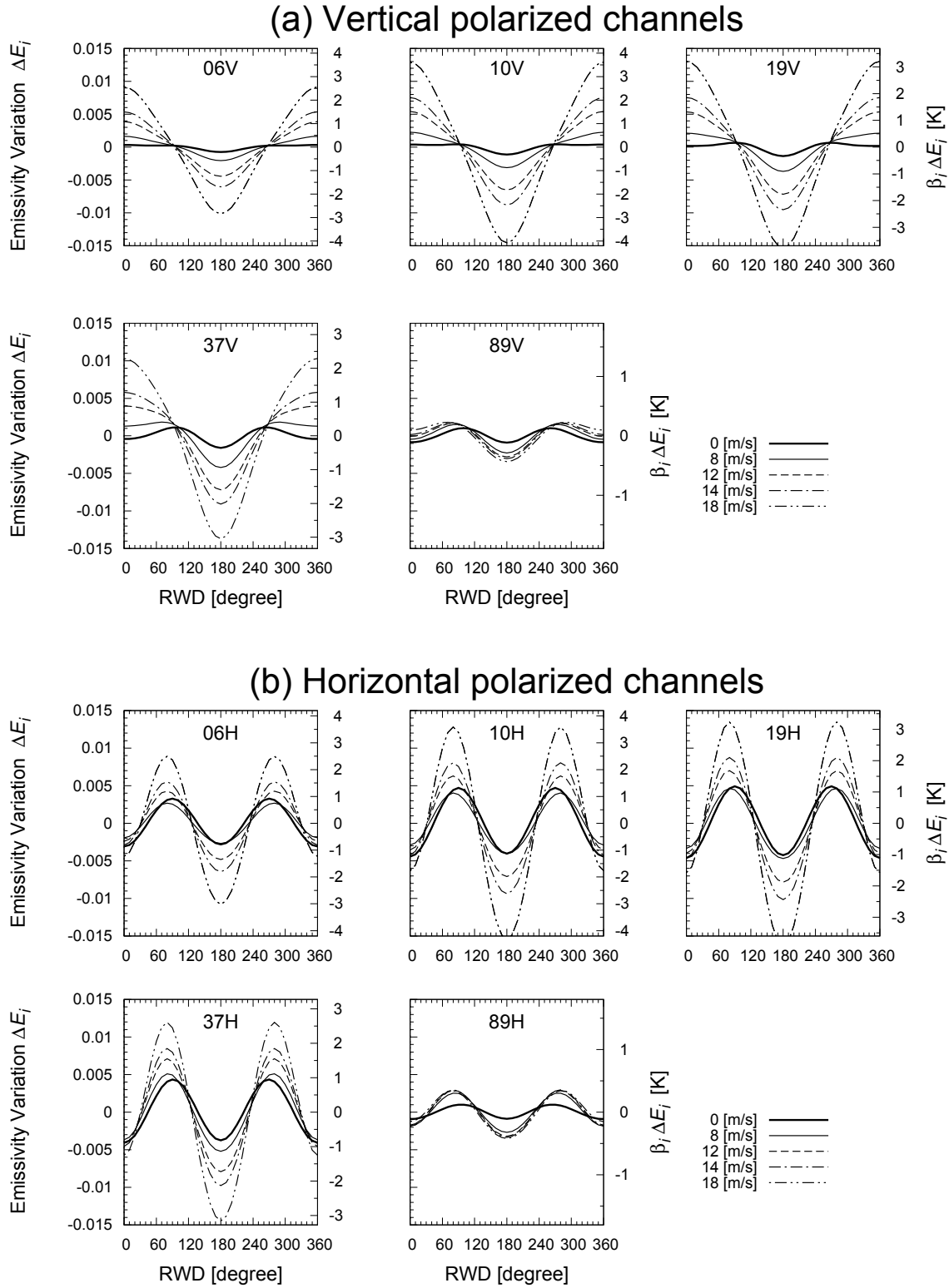


Figure 5.6. Same as Figure 5.4 but for FASTEM-5 azimuthal model function in CRTM.

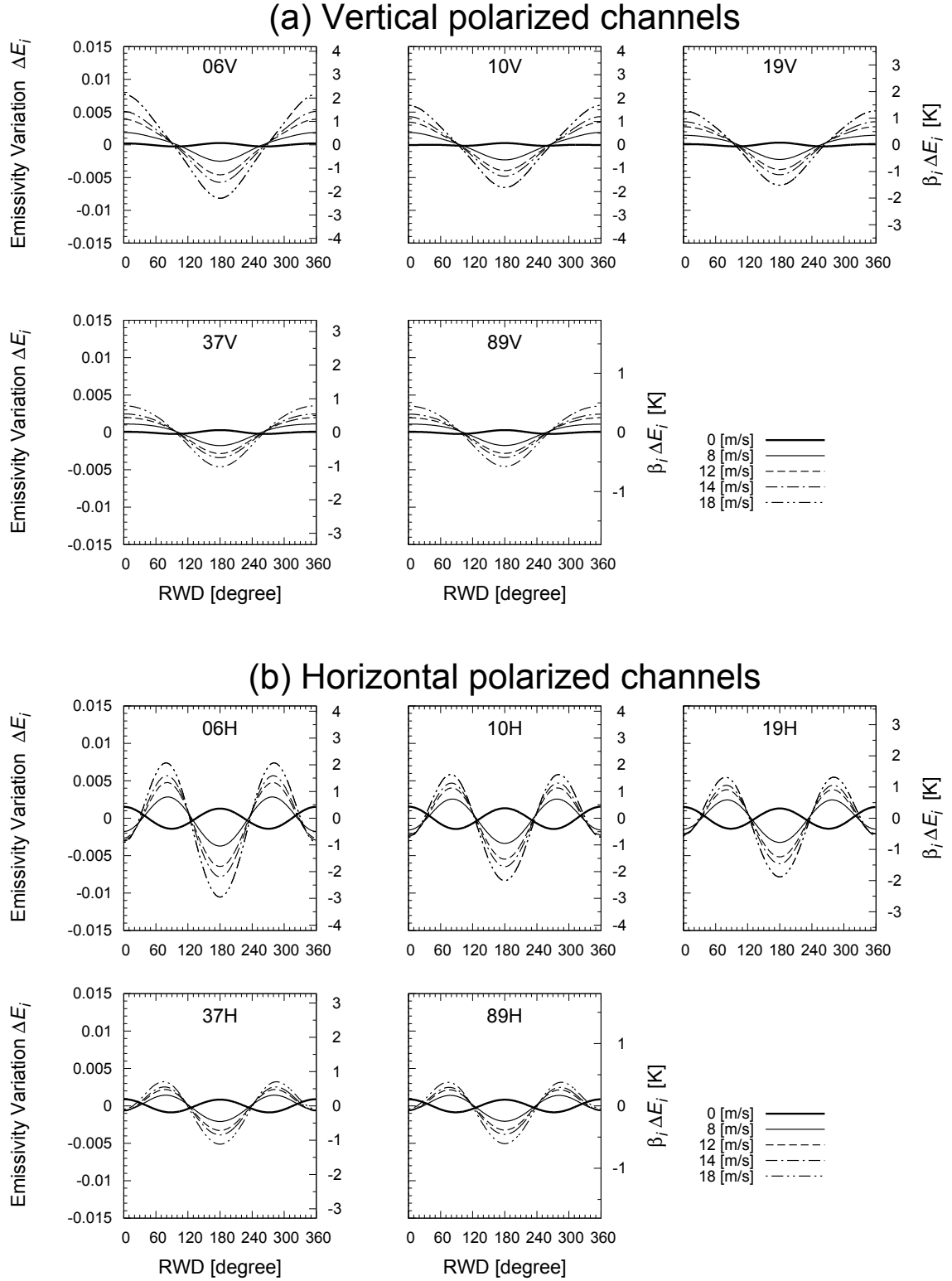


Figure 5.7. Same as Figure 5.4 but for FASTEM-3 azimuthal model function.

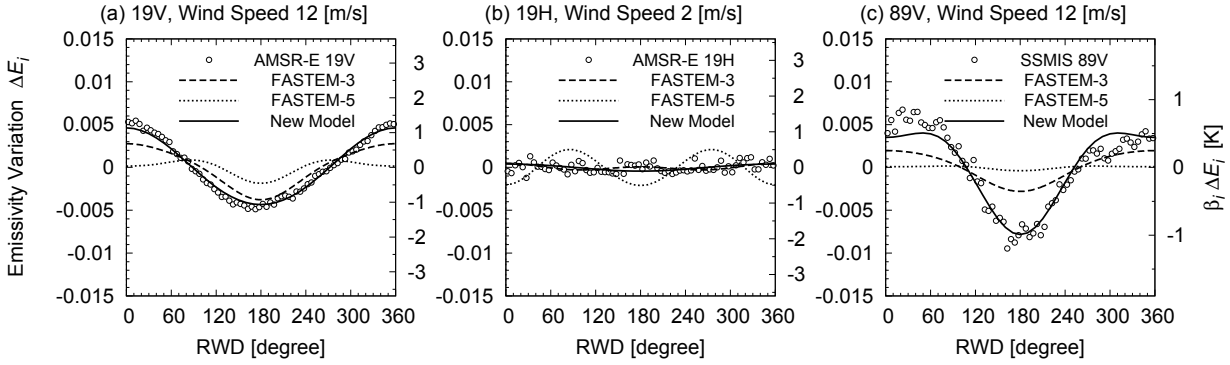


Figure 5.8. Comparisons of observed azimuth variation of the radiance and RWD models. (a) AMSR-E 19V at wind speed 12 m s^{-1} , (b) AMSR-E 19H at wind speed 2 m s^{-1} , (c) SSMIS 89V at wind speed 12 m s^{-1} .

5.3. Impact Study

5.3.1. Experimental Configuration

To examine the effect of the RWD model function in the data assimilation, data assimilation experiments in the ECMWF Integrated Forecast System (IFS) were performed. In ECMWF IFS, microwave imager radiance data are assimilated in an all-sky approach over ocean (Bauer et al., 2010; Geer et al., 2010; Geer and Bauer, 2011). The ECMWF IFS system (cycle 38r2: Bauer et al., 2013) uses RTTOV-10 (Saunders et al., 2012) as radiance observation operator in the data assimilation (Bormann et al., 2011). The FASTEM-5 azimuthal model function in RTTOV-10 was modified with the new RWD model function for one of the experiments (Test1). The Control run does not use the azimuthal function in FASTEM-5 for the microwave imagers. As for microwave sounders (e.g., AMSU-A, MHS), the azimuthal model function in FASTEM-5 is used in the Control run. These settings of the Control run are consistent with the operational ECMWF IFS configuration. The new RWD model function is used for both microwave imager and sounder instruments in Test1. Because the surface-sensitive channels (e.g., AMSU-A channels 1, 2, 3 and 4, MHS channels 1 and 2) are not actively assimilated in the ECMWF system, the change of the emissivity model for the microwave sounders should be minor, and major impact would be seen for the microwave imagers. As a comparison experiment, FASTEM-5 azimuth model function is used for microwave imagers and sounders in Test2.

Test1 uses the new RWD model function for all microwave sensors, and Test2 uses FASTEM-5 azimuth model function for all microwave sensors. The Control uses no RWD model for microwave imagers and FASTEM-5 azimuth model function for microwave sounders.

The input RWD for the models is the difference between first-guess wind direction and the satellite azimuth angle at the observation locations. SSMIS and TMI do not have azimuth angles available in the real-time dataset, so the angles were numerically calculated in house using the Kumabe and Egawa (2011) method from the satellite sensor position and scan geometry.

Observations used in the experiments are identical between the Test runs and the Control

run. Quality control, pre-screening and the forecast model are also identical among the three runs. The only difference is the use of the RWD model function in the radiative transfer calculation. The experiments were executed at T511 L137 resolution with cycle 38r2 configuration. This was the operational cycle at ECMWF in June 2013, but in the experiments it was run at approximately half the operational resolution. The experiment period was from 20 June to 3 October 2011. The forecasts from 0000 UTC initial times were produced every day during the period. Because three microwave imagers (AMSR-E, TMI and F17 SSMIS) were available in the experiment period, the large amount of radiance data would provide a strong test for the use of the RWD model function. The microwave imager channels 19V, 19H, 23V, 23H (for AMSR-E only), 37V and 89V were actively assimilated in the experiments. AMSR-E 89V and 89H channels were not available due to instrument issues during the period. In the ECMWF all-sky radiance assimilation scheme, horizontally polarized channels at 37 GHz and 89 GHz from microwave imagers are not assimilated.

5.3.2. FG Departure Comparison

The first guess (FG) is a short-range forecast (~ 12 h) valid at the time and location of the observations. FG departure is examined to investigate the impact of the RWD model function in the radiative transfer calculations. Figure 5.9(a) panels show bias (black dots for Test1 and open circle for Control) and standard deviation (solid bars for Test1 and grey bars for Control) for AMSR-E 19V FG departure at wind speed (4, 8, 10, 12, 14 and 16 m s^{-1}) categories. FG departure after variational bias corrections (VarBC: Dee, 2004) was used for these comparisons. In low wind-speed conditions (e.g., 4 m s^{-1}), the differences between Test1 and Control were small because the azimuthal variation itself was small. In high wind-speed conditions ($> 10 \text{ m s}^{-1}$), clear azimuthal variations in terms of RWD were found in the Control. This means the NWP FG wind field has sufficiently high accuracy in speed and direction to represent the azimuthal variation. The azimuthal variations in the biases were reduced in Test1. Figure 5.9(b) panels show the same results but for 19H. In high wind conditions (e.g., 16 m s^{-1}), the biases from the azimuthal variation reached about 2 K in the Control in both polarizations. However, in Test1, the RWD model function was able to represent the variation for both polarizations from the low to high wind-speed conditions and reduced the biases. Although the results in high wind conditions (Figure 5.9(b); 14, 16 m s^{-1}) show small remaining biases, generally most of the biases were reduced in Test1. Figure 5.9(c) panels indicate comparisons among different frequency (19V, 19H, 23V, 23H, 37V and 89V) at 12 m s^{-1} wind speed conditions. These microwave imager channels are actively assimilated in the ECMWF IFS. At 89V, the results for SSMIS were plotted instead of AMSR-E. For the frequency range from 19 to 91 GHz, the RWD model function reduced the biases and worked properly for AMSR-E, SSMIS and TMI. The results shown in Figure 5.9 are comparisons between using the new RWD model function and using no azimuth model function (i.e., Test1 and Control) for microwave imagers. Figure 5.10(a) compares results for AMSUA surface-sensitive channels using the new RWD model function (Test1) and the FASTEM-5 azimuth model function (Control). In the Control run, the FASTEM-5 azimuth model function is used

for microwave sounding sensors. Because AMSU-A is a cross-track scanning sensor, the incidence angle varies depending on the scan position, and the sensitivity to the surface wind also varies. These channels are not assimilated but their simulated radiance could be affected by the change of RWD model. No clear improvement was found for these channels but the new RWD model function appears to provide similar performance to FASTEM-5 here. Figure 5.10(b) shows comparisons between using the new RWD model and the FASTEM-5 azimuth model function for microwave imagers (Test1 and Test2). Larger bias reductions using the new RWD model function were confirmed.

Figure 5.11 (a,b) show geographical distributions of mean FG departure of assimilated F17 SSMIS 19V in the Control. Moreover, (c) and (d) show standard deviation of the FG departure. Figure 5.11 (a,c) are ascending data and (b) and (d) are descending data. In the Inter-tropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ), large positive biases (2 – 5 K) in FG departure were found for both ascending and descending orbit data (Figure 5.11 (a,b)). Moreover, in the ITCZ and SPCZ, the standard deviations were larger than in other areas. The reason for the positive biases and the large standard deviation relates both to the accuracy of the radiative transfer model and the forecast model under cloud and precipitation conditions. They are similar in ascending and descending orbits. Because larger observation errors are assigned for these data in the ECMWF all-sky radiance assimilation system (Geer and Bauer, 2011), these biases are not as important as they look. However, the FG departure bias in the Arabian Sea was orbit dependent. The sign of the bias was opposite between the ascending orbit (negative bias approximately 1.5 K) and descending orbit (positive bias approximately 1.0 K) while the standard deviations in the area were relatively small (less than 2 K) compared with other areas. The orbit-dependent biases are large and might have a negative impact on forecast quality in the Control run.

Figure 5.12 shows the difference of mean FG departure between the Test1 and Control runs for F17 SSMIS 19V (a) ascending and (b) descending data. The impacts of the RWD model function varied between regions and orbital direction in the SSMIS FG departures. Generally, the orbit-dependent biases of the microwave imagers in the Control run were reduced in Test1. The bias reduction in the Arabian Sea was remarkable. The bias reductions in the ascending and descending data in the Arabian Sea were approximately 0.6 and 0.7 K, respectively. Moreover, the biases in the northeast Pacific, southeast Pacific, and southeast Atlantic oceans were also reduced. The change in the Southern Hemisphere (close to 60°S and the southern extra-tropical storm track) were opposite between the ascending (negative) and the descending orbit (positive) because westerly winds were dominant in this area. Figure 5.12 (c,d) show the impact of RWD model function changes for Metop-A AMSU-A channel 5 ascending and descending data, respectively. Figure 5.12 (e,f) are Metop-A MHS channel 5. These are the lowest tropospheric microwave sounding channels for temperature and humidity respectively that are actively assimilated. Figure 5.12 (c–f) does not show any surface-related geographical pattern either in ascending or descending data. Figure 5.13 shows the same comparisons but for AMSU-A surface-sensitive channels (channel 1, 2, 15). The impacts of RWD model changes were found as bias changes in low to moderate wind speed areas in the Tropics, especially in channel 2 (31.4 GHz). However, because the window channels of

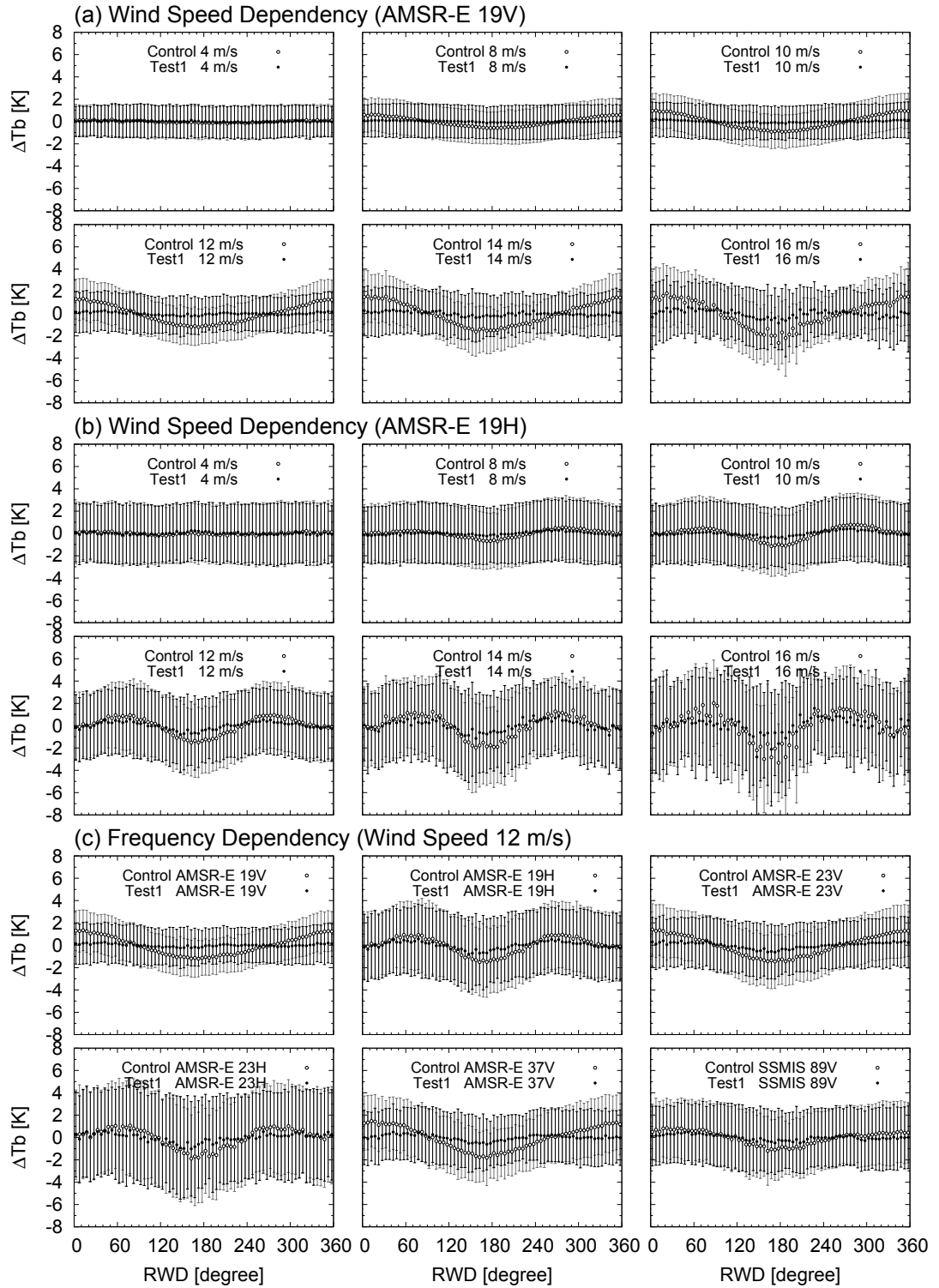


Figure 5.9. Comparisons of FG departure in terms of RWD between Test1 and the Control run for microwave imagers. The biases (Test 1: filled circles, Control: open circles) and the standard deviations (Test1: solid bars, Control: grey bars) are displayed. (a) AMSR-E 19V channel at 4, 8, 10, 12, 14, 16 m s^{-1} surface wind speed, (b) same as (a) but for AMSR-E 19H channel, (c) AMSR-E for 19V, 19H, 23V, 23H, 37V and SSMIS for 89V. These are comparisons between RWD model function and no azimuth model function.

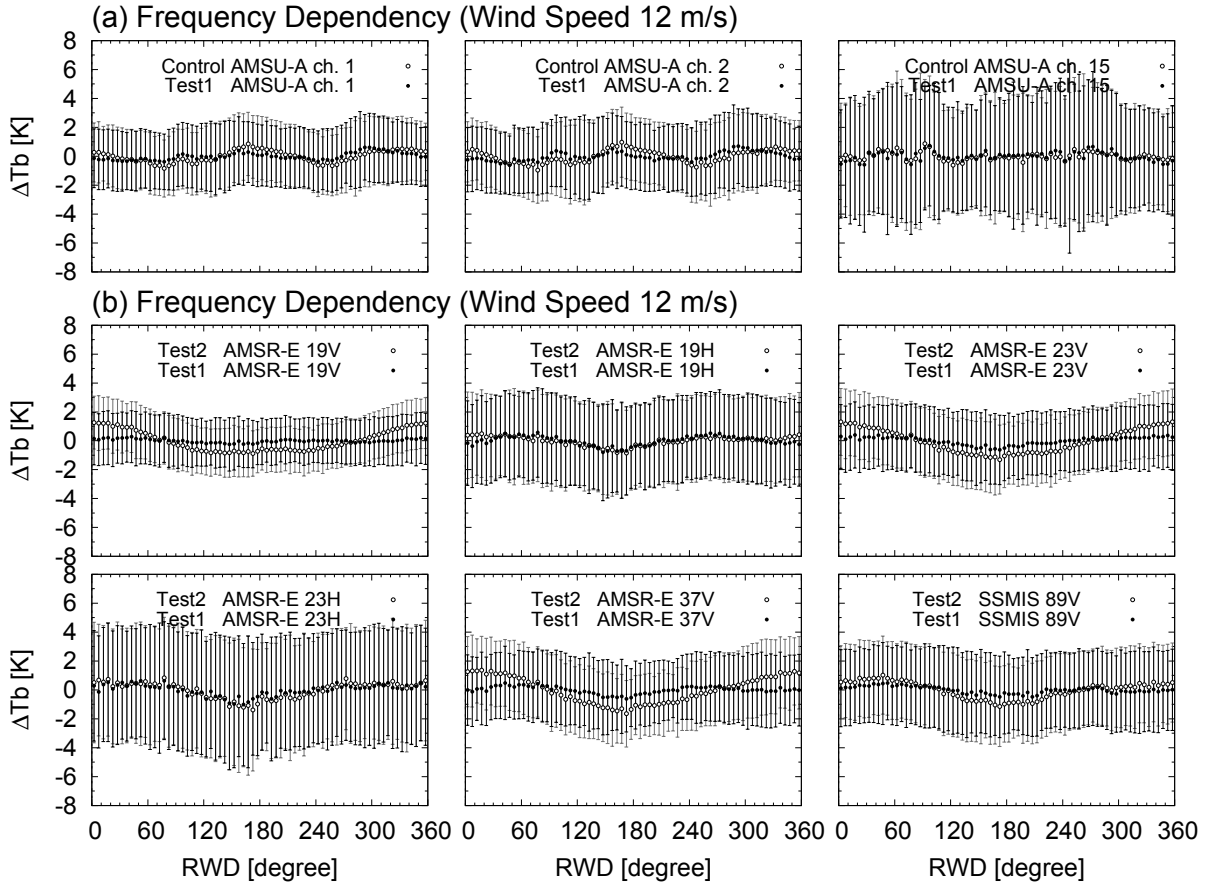


Figure 5.10. (a) Comparisons of FG departure in terms of RWD between Test1 and the Control run for surface-sensitive microwave sounder channels. The biases (Test1: filled circles, Control: open circles) and the standard deviations (Test1: solid bars, Control: grey bars) are displayed for Metop-A AMSU-A channels 1, 2 and 15 at surface wind speed 12 m s^{-1} . These are comparisons between the new RWD model function and FASTEM-5 azimuth model function. (b) Comparisons of microwave imager FG departure between the new RWD model function (Test1: filled circles) and FASTEM-5 (Test2: open circles) for AMSR-E 19V, 19H, 23V, 23H, 37V and SSMIS 89V at 12 m s^{-1} surface wind speed.

CHAPTER 5. USE OF THE OCEAN SURFACE WIND DIRECTION SIGNAL IN MICROWAVE RADIANCE ASSIMILATION

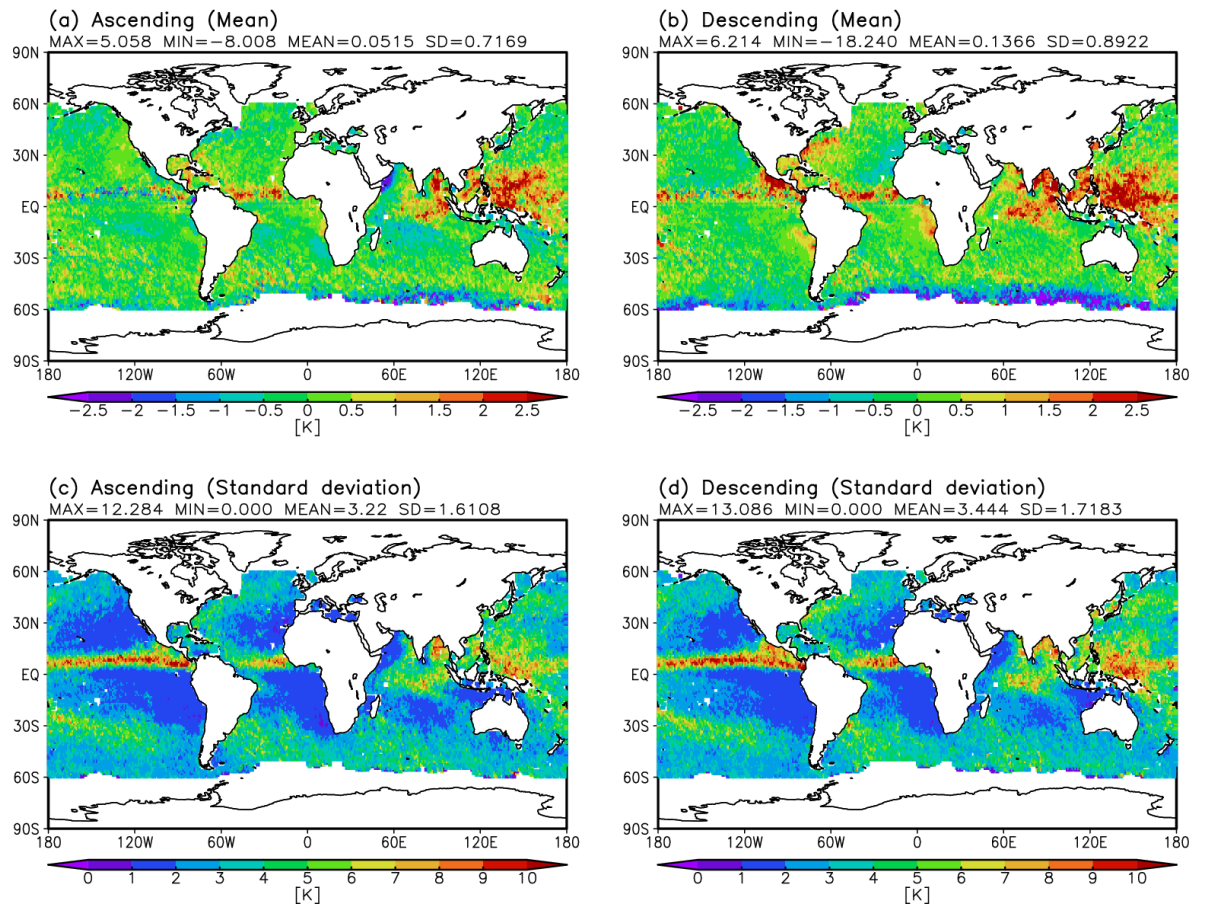


Figure 5.11. Mean and standard deviation of FG departure of F17 SSMIS 19V channel from the Control run in the experiment period. The ascending data are (a) mean, (c) standard deviation. The descending data are (b) mean, (d) standard deviation.

the microwave sounding instruments are only used for cloud detection when assimilating the lower tropospheric channels in the ECMWF system, the differences of the assimilated data counts between the Test1 and Control runs were very small (e.g., approximately 0.05% difference for AMSU-A channel 5 and 0.01% difference for the MHS channel). The impacts of the RWD model function were minor for the assimilated microwave sounding data. However, major impacts were found for the microwave imager data. In other words, the impacts were found in surface-sensitive channels in the microwave frequency range from 19 to 89 GHz.

To confirm the relationship of the changes in the FG departure biases of the microwave imager channels and the surface wind field, the monthly mean 1000 hPa wind field for August 2011 from the analysis in Test1 is shown in Figure 5.14. In the experiment period (boreal summer), the strong south-westerly winds (Somali jet) in the Arabian Sea are clearly seen. The Somali jet is a high-wind-speed meteorological phenomenon with mean winds of more than 12 m s^{-1} from June to September every year. Moreover, this area is generally cloud-free in the boreal summer. The microwave imagers observe the surface directly without any cloud and rain contamination. The negatively biased area shown in Figure 5.11(a) has a good agreement with the high-wind area ($> 10 \text{ m s}^{-1}$) in Figure 5.14. Moreover, other large difference areas in FG departure seen in Figure 5.12 (a,b) correspond to areas with high wind-speed and low wind-direction variability.

Figure 5.15 shows reductions in the standard deviation of FG departures of the microwave imagers (AMSR-E, TMI and SSMIS) for three regions (Northern Hemisphere, Tropics and Southern Hemisphere). The standard deviations have been normalized by the value of the Control run and are shown in percentage terms. Panels (a), (b) and (c) are for Test1, and panels (d), (e) and (f) are for Test2. Generally, the global standard deviations of FG departures were reduced in Test1. The reduction of FG departures of vertically polarized channels in the Southern Hemisphere was significant. One reason for the larger impact is that high wind speed areas occur more often in the Southern Hemisphere than in mid- and low- latitudes during the experiment period. The results in Test2 show less impact in the FG departure.

Figure 5.16 shows (a), (b) the satellite azimuth angle, and (c), (d) the relative wind direction for AMSR-E for the Arabian Sea. Although this is a single day in the experiment period, the pattern of the satellite azimuth angle and the RWD are similar during the period because conical scanning microwave imagers on polar-orbiting satellites observe the area with this fixed geometry every orbit. For the Arabian Sea, the value of RWD in ascending orbit (Figure 5.16(c)) is from 180 to 240° (downwind direction) and that in descending orbit (Figure 5.16(d)) is around 0 or 360° (upwind direction). The azimuthal variation in term of RWD has a minimum in the downwind direction (19V) and a maximum in the upwind direction as shown in Figure 5.2(a). The orbit-dependent biases shown in Figure 5.11 were caused by non-modeling of RWD variation in the Control run. In Test1, the biases caused by the azimuthal variation were reduced with the RWD model function in the radiative transfer calculations.

CHAPTER 5. USE OF THE OCEAN SURFACE WIND DIRECTION SIGNAL IN MICROWAVE RADIANCE ASSIMILATION

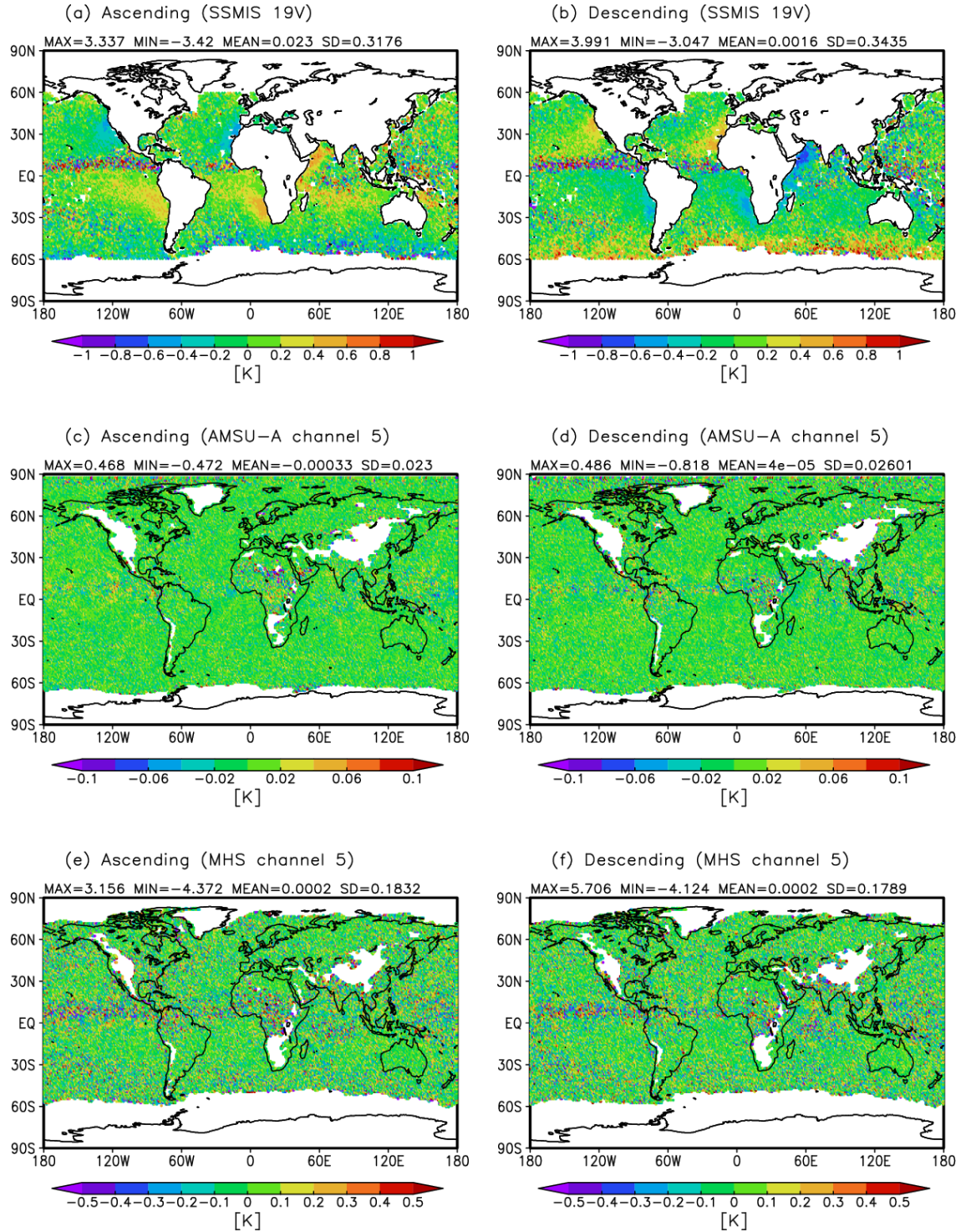


Figure 5.12. Mean difference of FG departure of assimilated data between Test1 and Control in the experiment period. (a) F17 SSMIS 19V ascending data, (b) descending data, (c) Metop-A AMSU-A channel 5 ascending data, (d) descending data, and (e) Metop-A MHS channel 5 ascending data, (f) descending data. The comparison is between the new RWD model function and no azimuth model function.

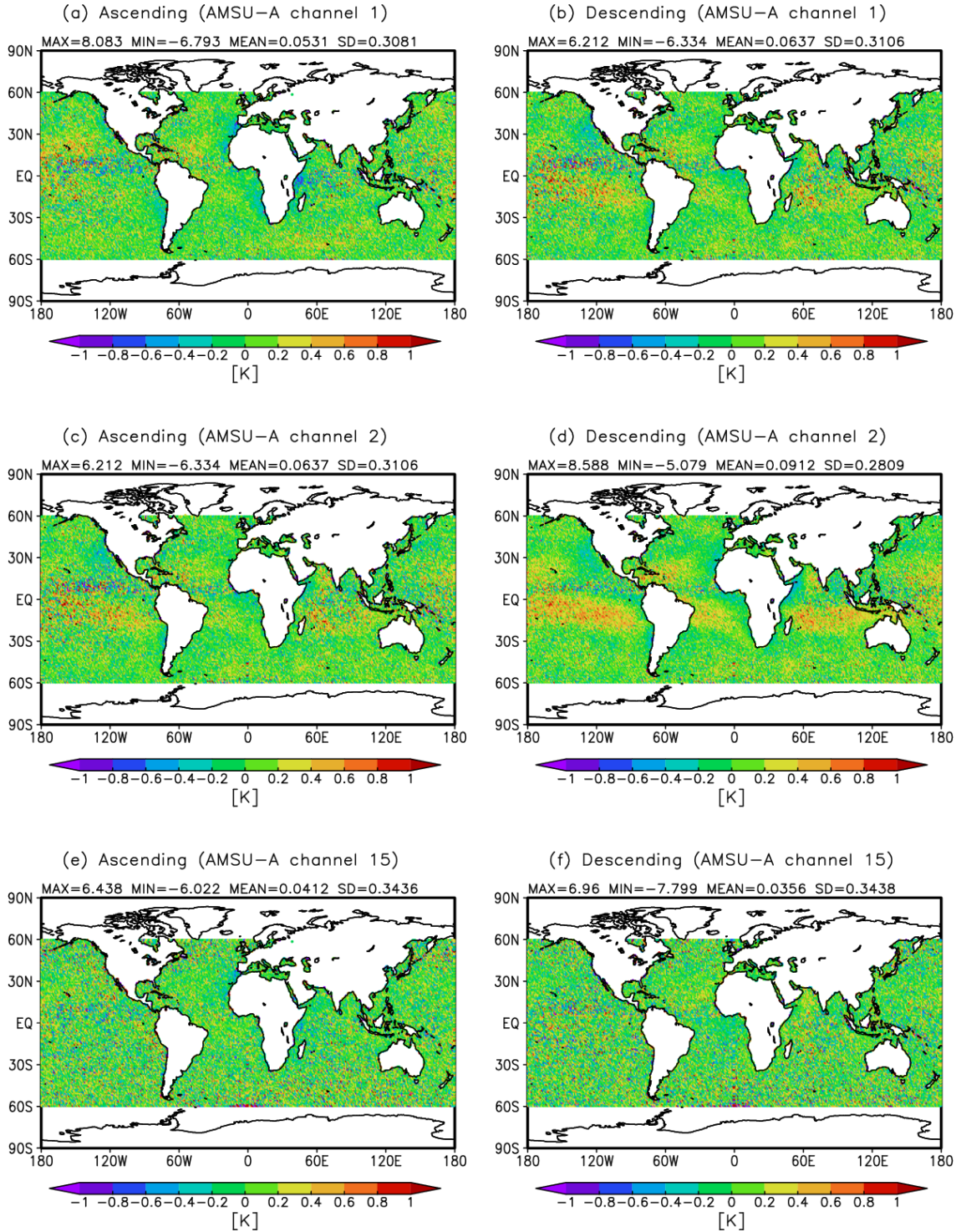


Figure 5.13. Mean difference of FG departure of surface-sensitive channels of Metop-A AMSU-A between Test1 and Control in the experiment period. (a) Channel 1 (23.8 GHz) ascending data, (b) Channel 1 descending data, (c) Channel 2 (31.4 GHz) ascending data, (d) Channel 2 descending data, and (e) Channel 15 (89.0 GHz) ascending data, (f) Channel 15 descending data. The comparison is between the new RWD model function and FASTEM-5 azimuth model function.

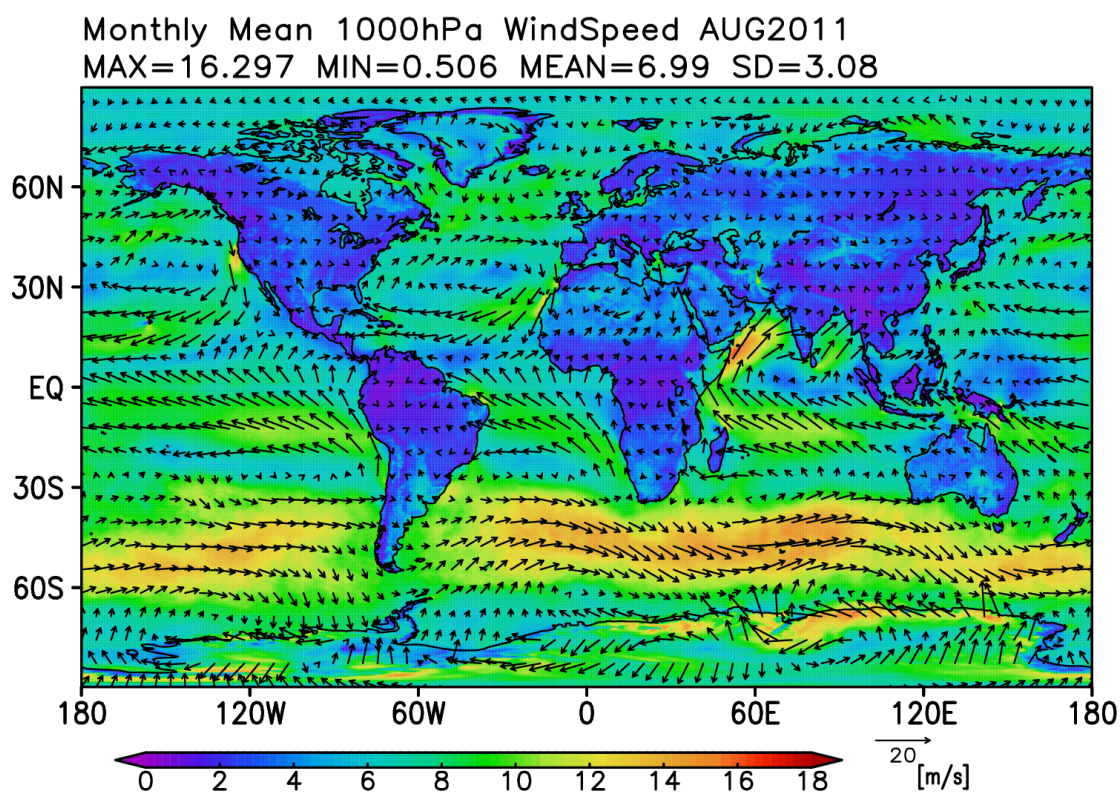


Figure 5.14. Monthly mean wind field at 1000 hPa for Aug 2011 in Test1.

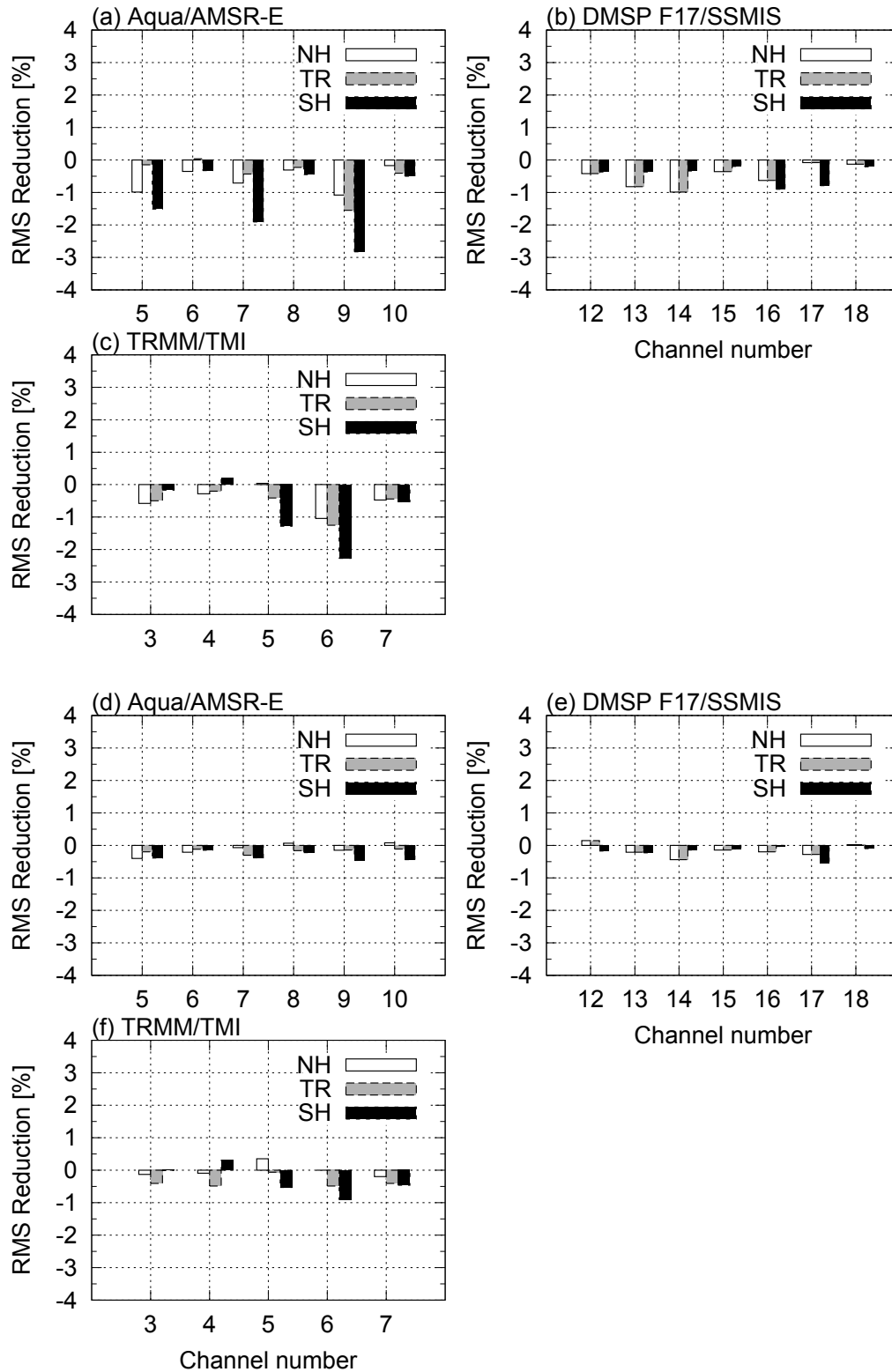


Figure 5.15. Reduction of standard deviation of FG departures of the microwave imagers. Standard deviations have been normalized by the value of the Control run and shown in percentage terms. (a) AMSR-E, (b) F17 SSMIS and (c) TMI from Test1. Panels (d – f) are the same but from Test2. White is the Northern Hemisphere, grey is the Tropics, and black is the Southern Hemisphere.

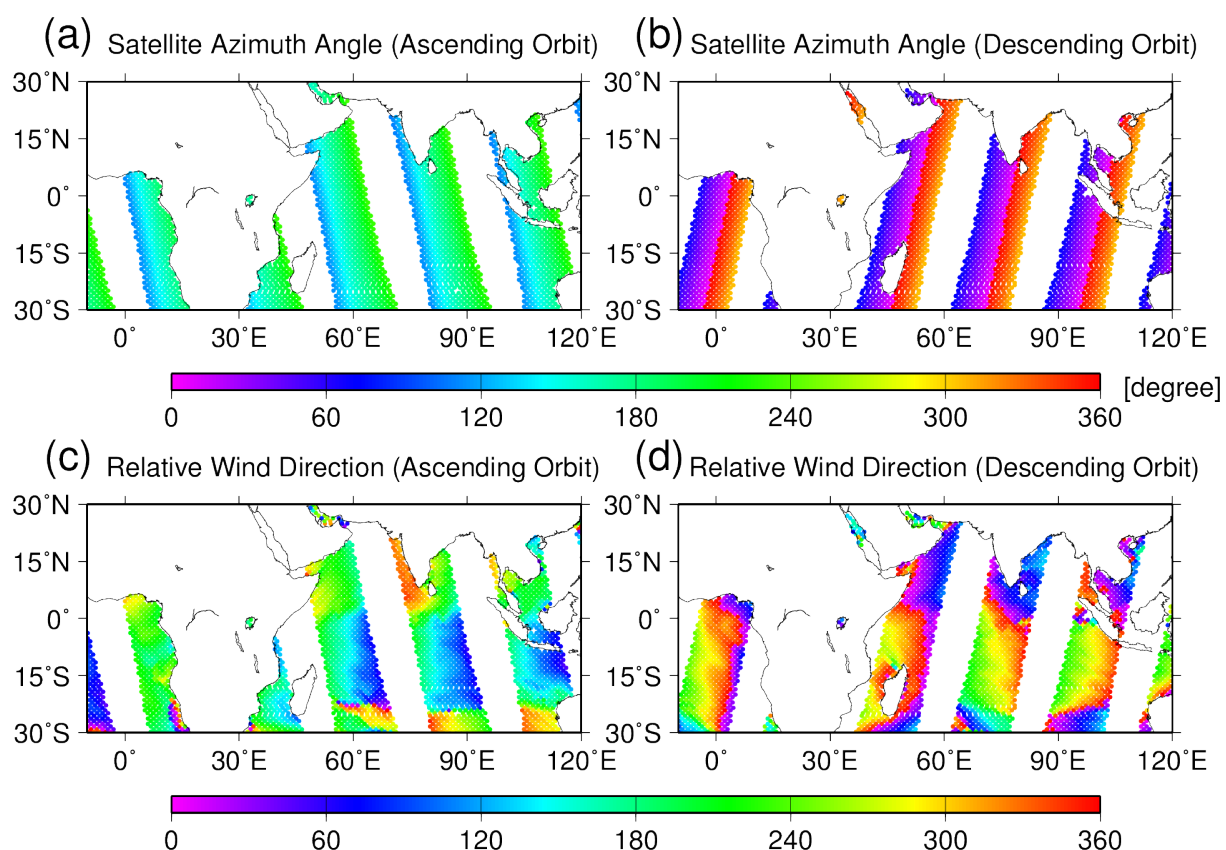


Figure 5.16. An example of AMSR-E satellite azimuth angle in the Arabian Sea. (a) Ascending orbit, (b) descending orbit. RWD distribution (c) ascending orbit, (d) descending orbit in the experiment. The units are degrees. An RWD of 0 or 360° corresponds to the upwind direction and 180° corresponds to the downwind direction.

5.3.3. Impacts on Atmospheric Analysis and Forecast

The microwave imager channels (19V, 19H, 23V, 23H, 37V and 89V) have strong sensitivity not only to surface wind but also to atmospheric humidity and cloud in the lower troposphere. The humidity information obtained from the microwave measurements plays an important role in the humidity analysis and forecast. As most of the water vapor amounts are concentrated in the lower troposphere, mean differences of the RMS of analysis increments on the 1000 hPa specific humidity for Test1 (Figure 5.17(a)) and Test2 (Figure 5.17(b)) were investigated. The largest reduction of the RMS of the analysis increment was found for the Arabian Sea (approximately 0.2 g kg^{-1}) in Test1. In the high-latitude areas in the Southern Hemisphere (along the storm track), the impact was small compared with other high-wind-speed areas. Although there are high-wind areas in the Southern Hemisphere, many microwave imager observations are not used because of large positive biases caused by a lack of cloud liquid water in cold sectors (Geer and Bauer, 2011) in the ECMWF forecast fields. The impacts on the analysis were small in the Test2 case.

The use of the RWD model function brought improvements in the forecast in Test1. Figure 5.18 shows normalized differences of RMS error of relative humidity (RH) and temperature (T) forecasts. The forecasts were verified against the experiment's own analysis. Blue colors indicate a reduction in the forecast error arising from the use of the RWD model function in the radiative transfer calculations. In the Southern Hemisphere lower troposphere, significant error reductions in RH and T were found for short-range forecasts in Test1. The improvements of the RMS error at 12 h forecast indicate reductions of analysis increments of RH and T in the data assimilation. The impacts on the forecast were small in the Test2 case.

Figure 5.19 shows the normalized RMS error difference of RH as a function of forecast time for three pressure levels (500, 850 and 1000 hPa). Significant improvements were found in the Southern Hemisphere and the Tropics in the short-range forecasts for Test1 (solid circles). The results from Test2 are shown in open circles. The improvements in the Southern Hemisphere lower troposphere in Test1 were retained until day 3 of the forecast.

Figure 5.20 is as Figure 5.19 but for temperature forecasts in the lower troposphere. Significant improvements of the temperature were found in the Southern Hemisphere and the Tropics in Test1. However, the improvements were limited in day 1 of the forecast. The results indicate the improvements in the short-range forecast could have been driven by the reductions of the humidity analysis increment in the data assimilation with the new RWD model function.

5.4. Summary

In this study, the wind directional signals in the oceanic microwave radiance data were focused. The azimuthal variation is a well-known phenomenon and many applications in remote sensing utilize it in geophysical product retrievals. However, the wind direction signals have not been actively taken into account in the radiative transfer calculation in data assimilation. ECMWF IFS FG fields do have sufficient accuracy to detect the azimuthal variation in the FG

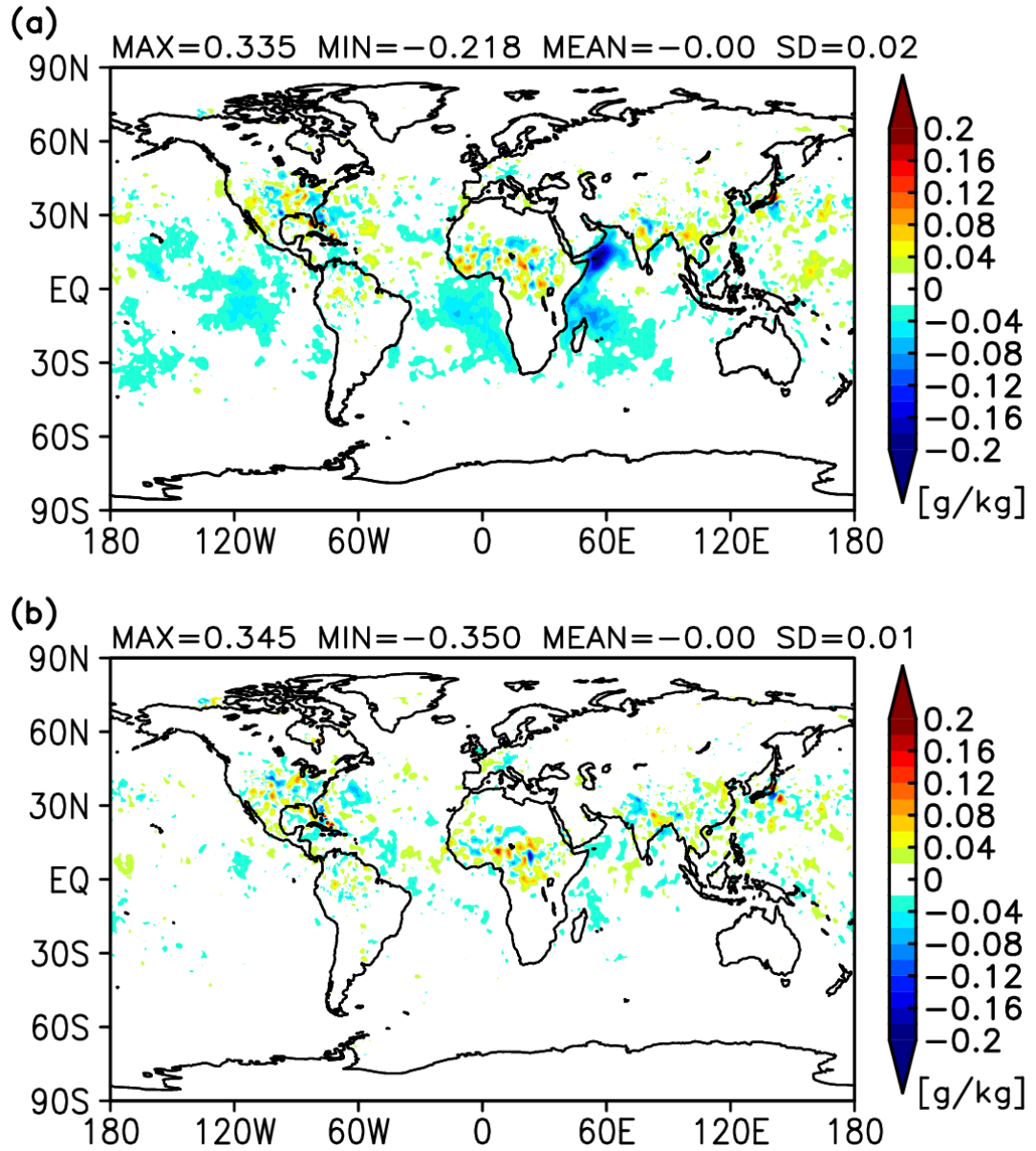


Figure 5.17. Mean RMS difference of 1000 hPa specific humidity analysis increment between the Test run and the Control run. (a) Test1, (b) Test2. Blue colors indicate a reduction in the analysis increment in the Test runs. The units are g kg^{-1} .

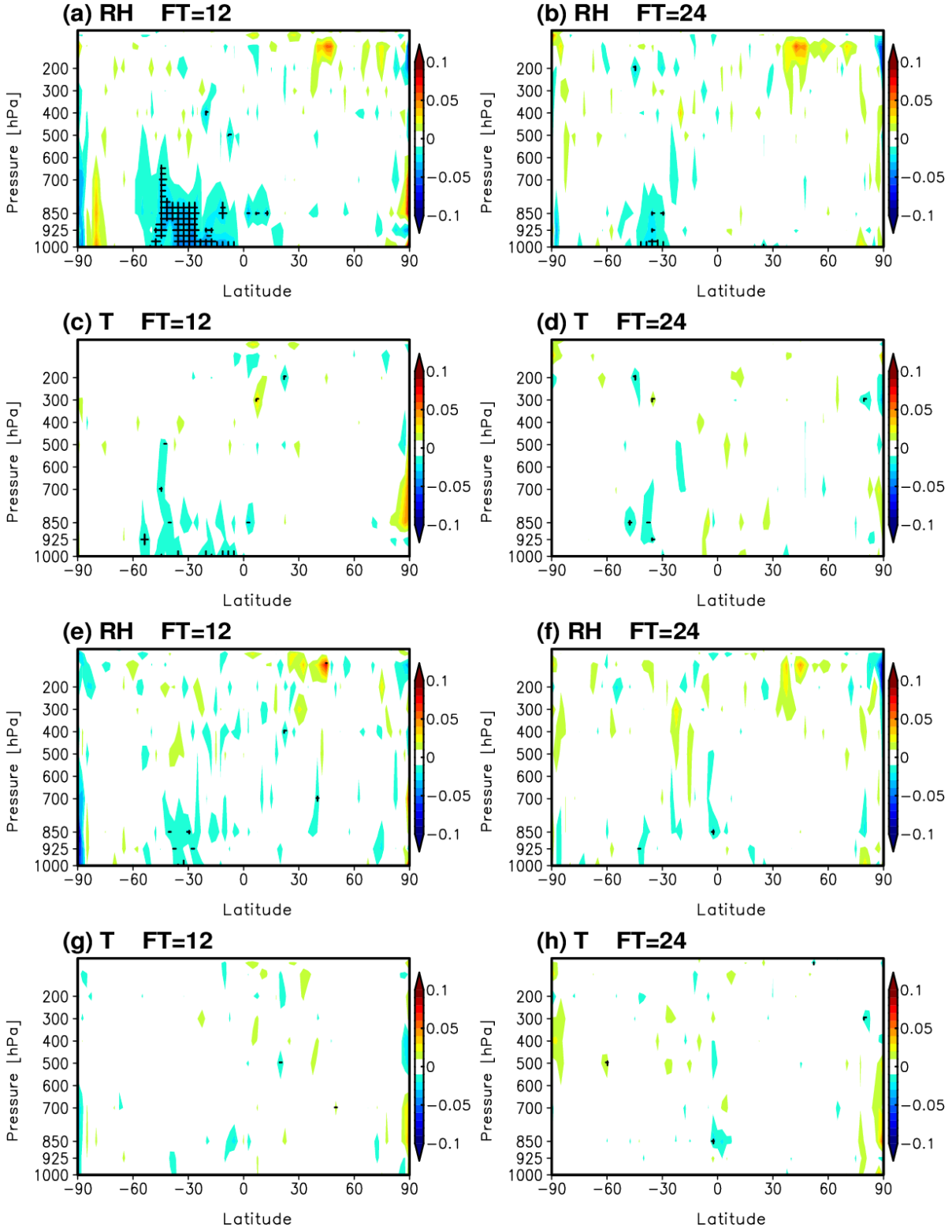


Figure 5.18. Normalized difference in relative humidity (RH) and temperature (T) forecast error (RMS) for 12 and 24 h forecasts. The top row is for relative humidity: (a) 12 h forecast, (b) 24 h forecast from Test1. Panels (c,d) are for temperature: (c) 12 h forecast, (d) 24 h forecast from Test1. Panels (e - h) are the same but from Test2. Cross-hatching indicates 95% statistical significance.

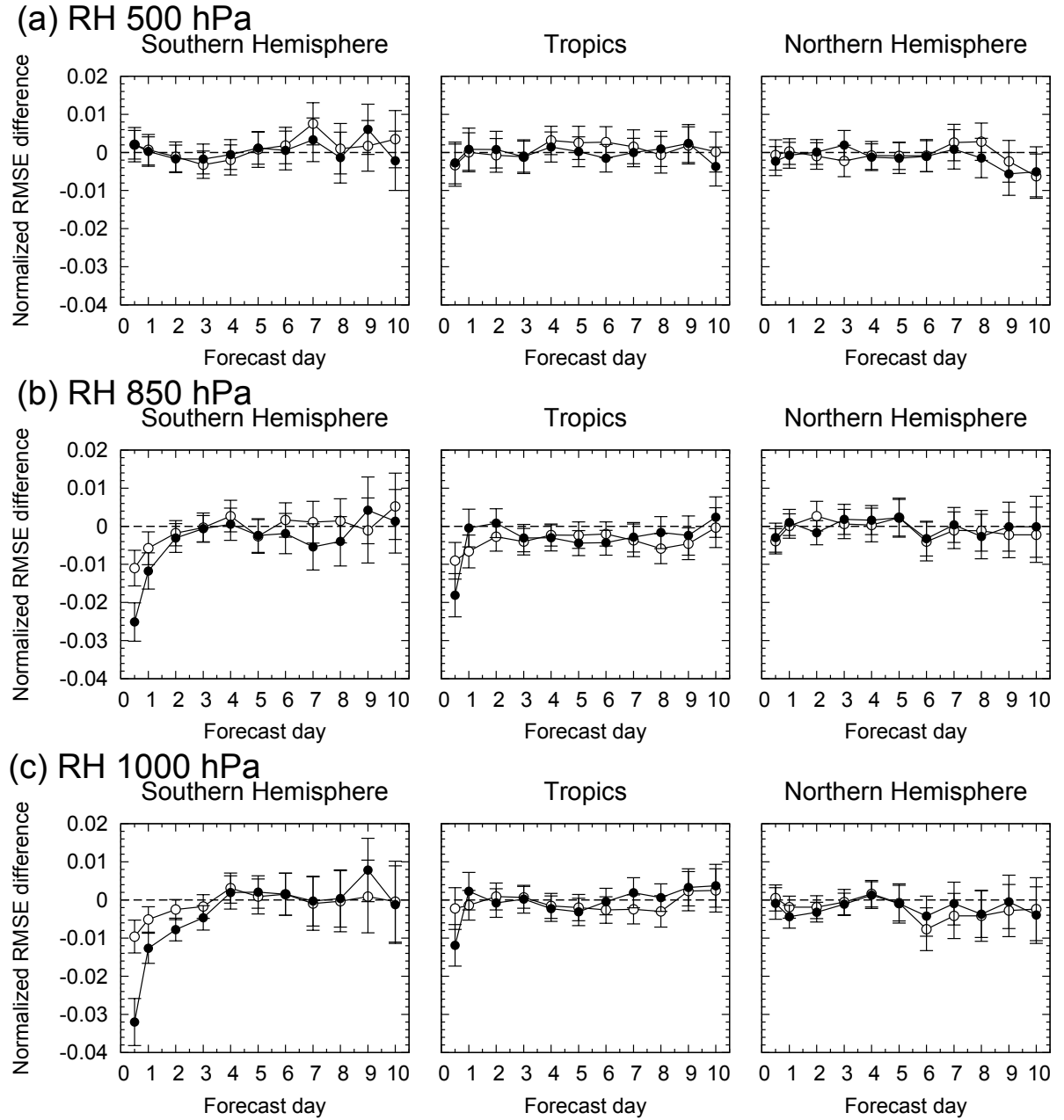


Figure 5.19. Normalized change in RMS forecast error in relative humidity at (a) 500 hPa, (b) 850 hPa, and (c) 1000 hPa for the Southern Hemisphere (latitudes -90 to -20), Tropics (latitudes -20 to 20), and Northern Hemisphere (latitudes 20 to 90). Verification is against own analysis. Scores are based on the experiment period 20 Jun to 3 Oct 2011. Error bars indicate the 95% confidence level. Solid circles are Test1 (the developed RWD model function), open circles are Test2 (FASTEM-5 azimuth model function).

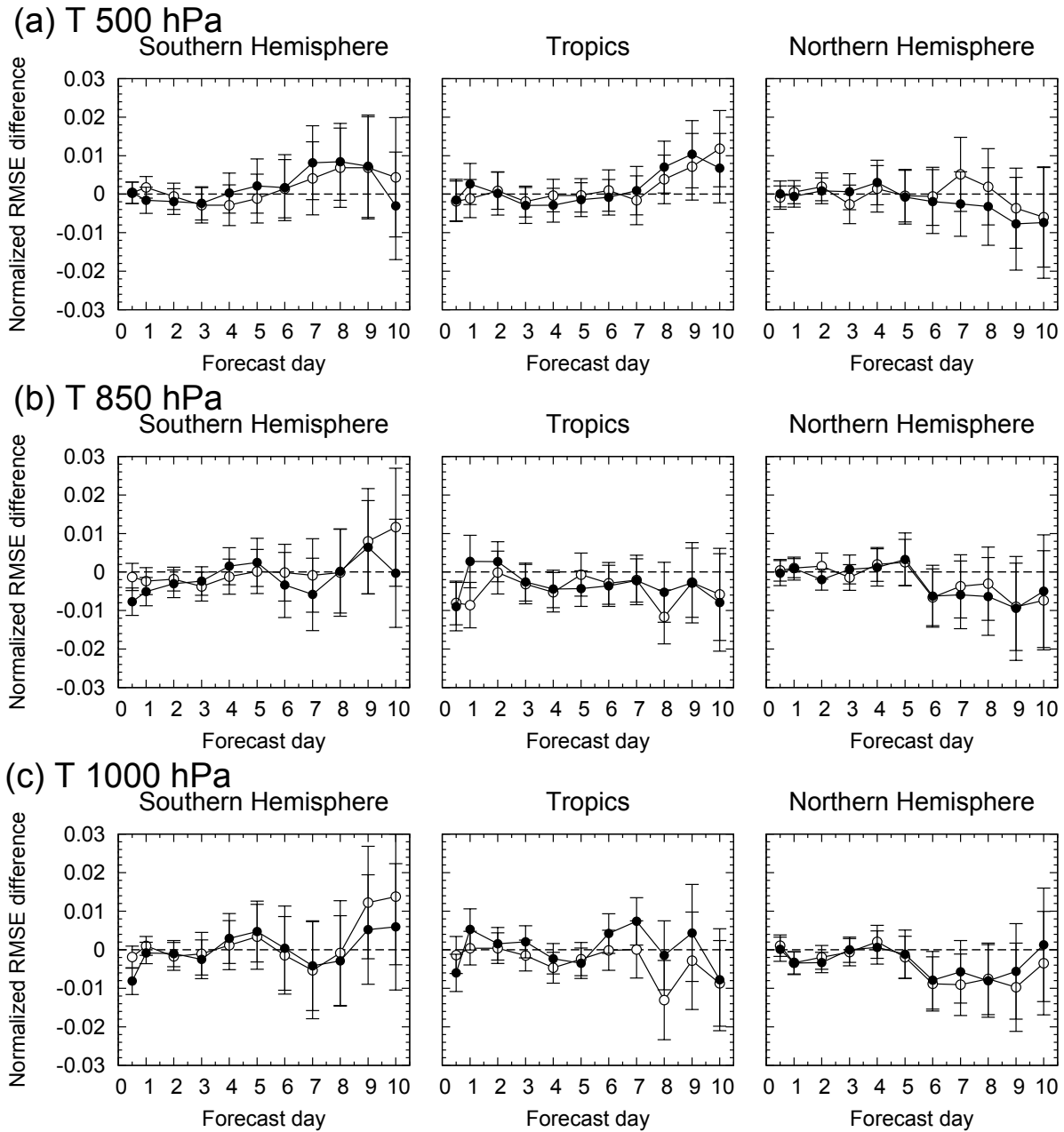


Figure 5.20. Same as Figure 5.19 but for temperature.

departure.

To utilize the wind direction signal in the data assimilation, a new Relative Wind Direction (RWD) model function was developed for the emissivity model. The development was based on simultaneous measurements of microwave radiance and surface wind vector from ADEOS-II AMSR and SeaWinds. Cloud-free conditions were selected to separate the surface signals and the atmospheric signals in the observations. As for cloud sensitive channels (89V and 89H), all-sky SSMIS data were used. The developed RWD model function was incorporated into the microwave ocean emissivity model (FASTEM-5) in RTTOV-10 for the impact study.

Input RWD was calculated from the surface wind vector in the FG field and the satellite azimuth angle. Because the satellite azimuth angles of SSMIS and TMI were not available in the real-time data in ECMWF IFS, the angles were calculated from the satellite position and the scan geometry in house. As the azimuth angle information is one of the basic satellite parameters for the radiative transfer calculation and other remote sensing applications, the information should be included in the operational dataset by space agencies for future microwave imagers.

The RWD model function performances were different from those of FASTEM-5 (in RTTOV and CRTM) and FASTEM-3. In the experiments, the performance of the new RWD model function brought reductions of the FG departure biases while FASTEM-5 azimuth model function brought smaller bias reductions than those of the new RWD model function. It was difficult to reduce the bias in the RWD space by small amplitudes of FASTEM-5 azimuth model function in RTTOV, and the unphysical wind direction sensitivity at low wind-speed of FASTEM-5 and -3 could have negative impact. Because the new RWD model function is based on real satellite measurements and less sensitivity at zero wind speed, it provided better performance than other models. This is confirmed in the comparison with real observations. The model function can be used for microwave imagers (e.g., AMSR-E, SSMIS and TMI) and temperature sounders (e.g., AMSU-A). The new RWD model function reduced the FG departure biases, especially in high wind speed and low wind direction variability areas (i.e., Arabian Sea, northeast Pacific, southeast Pacific, southeast Atlantic oceans) for the microwave imagers. The impacts for the microwave sounding channels for the assimilation were minor, but AMSU-A channel 2 (31.4 GHz) showed bias changes in low and moderate wind-speed areas.

The orbit-dependent biases of the microwave imagers in the Control run were caused by non-modeling of the azimuthal variation in the emissivity calculations. However, the experiment run using the new RWD function had lower biases. This is confirmed from the reduction of the analysis increment of the specific humidity at 1000 hPa. The changes in high wind-speed areas led to a significant improvement in RMS errors of the relative humidity and temperature fields in the lower troposphere for short-range forecasts.

The changes in FG departure using the new RWD model function were consistent with wind field and satellite azimuth angle relationships. Currently, the use of microwave imager radiance data in the Southern Hemisphere is limited due to cold sector biases (Geer and Bauer, 2011) in the ECMWF system. To enhance the use of the microwave imager data in the high-latitude areas in future, the azimuthal variation should be treated with an accurate RWD model

function in the radiative transfer model. The experiment results clearly showed the importance of the modeling of the azimuthal variation in the microwave radiance assimilation. The RWD model function should be in the radiative transfer model both for present microwave imagers and for upcoming new sensors, e.g., Global Change Observation Mission - Water1 (GCOM-W1) AMSR2 and the Global Precipitation Measurement Microwave Imager (GMI). The new RWD model function, combined with the other components of FASTEM-5, is available as FASTEM-6 in RTTOV.

6. General Conclusions and Future Prospects

This thesis describes scientific research undertaken for the purpose of improving weather forecasting. To achieve this purpose, three studies were carried out on NWP forecasts with satellite radiance assimilation experiments.

The first study introduced direct radiance assimilation into the JMA mesoscale NWP system. Direct radiance assimilation replaced retrievals of temperature and total precipitable water with original radiance data. A number of new radiance data were incorporated into the NWP system without any retrieval process. The direct use of radiance data requires a radiative transfer model to extract the observation information from the radiance data in the data assimilation process. In particular, in the first study, the direct use of radiance data brought significant improvement to the accuracy of NWP forecasts. Microwave radiance data (temperature information from sounding instruments and humidity information from imager instruments) were the dominant contributors to the improvement of the geopotential height and precipitation forecasting skill in the JMA mesoscale NWP system.

The second study was the development of an ocean surface emissivity model for radiance data assimilation by low-frequency microwave channel's. A new ocean emissivity model was developed with empirical fittings to satellite microwave radiance observations. Moreover, the emissivity model was used in the radiative transfer calculation in data assimilation experiments. The performance of the developed emissivity model was better than the present operational model FASTEM-1 in the NCEP global data assimilation system. In particular, the biases of simulated radiance that depend on the ocean surface wind speed were greatly reduced. The AMSR-E radiance data assimilation experiments in the NCEP global NWP system demonstrated improvement of NWP model forecasting skill. In addition, the use of the new ocean emissivity model demonstrated better tropical cyclone forecasts for hurricane Katrina, whereas the operational emissivity model FASTEM-1 degraded the forecasts. The results clearly demonstrated that the new information from radiance observation in AMSR-E low-frequency channel's (i.e., surface wind speed under cloudy conditions) improved the NWP model forecasting skill. Furthermore, the results show that for the proper extraction of ocean surface wind speed information in microwave radiance assimilation, an accurate ocean emissivity model is crucial.

The third study was the development of an ocean surface emissivity model to represent the relative wind direction effect in microwave imager radiance data. This effect is a well-known phenomenon in the geophysical parameter retrieval community and is considered as an error source in the retrieval of various geophysical parameters (i.e., sea surface wind speed,

sea surface temperature, and atmospheric water vapor) from microwave imager radiance. Although this effect becomes larger under high surface wind speed conditions, there has been no investigation of the impact of this effect on microwave radiance data assimilation. Because the accuracy of the analysis field in high surface wind conditions is critical for high impact weather forecasts, it must be investigated. In the development of the new ocean surface emissivity model, simultaneous measurements of the radiance and the sea surface wind vector from AMSR and SeaWinds on the ADEOS-II satellite, and the wind vector from the ECMWF all-sky NWP system, were used. The new model can represent the relative wind direction effect realistically and is physically consistent (i.e., there is no RWD effect in calm ocean). Furthermore, the azimuthal variations of microwave imager radiance under high surface wind conditions were accurately represented. An impact study with the new ocean surface emissivity model demonstrated bias reductions in the simulated radiance in high wind speed and low wind direction variability areas (e.g., Somali Jet in the Arabian Sea). The use of the direction signal of ocean surface wind brought significant improvements in temperature and relative humidity forecasts in the ECMWF NWP system.

The contributions of this thesis to the progress of microwave radiance data assimilation for NWP models are summarized here. (i) Extension of microwave radiance assimilation to regional models. This is a new stage for satellite data assimilation in regional models because the contribution of satellite data to the accuracy of analyses and forecasts becomes greater than that of the previous retrieval assimilation stage. Although the use of radiance is presently limited to clear sky conditions, this is a necessary step toward advanced cloud- and rain- affected radiance assimilation. These results demonstrate a large potential for further improvement in forecasting accuracy in the future. (ii) Development of two microwave ocean emissivity models to extract ocean surface information from microwave radiance through the data assimilation process. The target information is surface wind speed and wind direction. For microwave imager observations, the primary observation information is atmospheric water vapor. This information is widely utilized in remote sensing applications. However, ocean surface information in the observations has not been examined in radiance data assimilation. In this research, the information was successfully extracted with ocean emissivity modeling of the microwave radiance variation. Moreover, the use of emissivity models together with microwave radiance observations in data assimilation substantially improved NWP forecasting accuracy. This is evidence that the ocean emissivity model can represent the variation of the microwave radiance caused by meteorological conditions. Therefore, it is concluded that the main purpose of this research was successfully achieved.

From a practical perspective, this thesis contributes to the improvement in accuracy of operational weather forecasting. The achievement of the first study has been implemented and used in JMA operational mesoscale system since December 2010. The two emissivity models are implemented in U.S. and European global data assimilation systems for operational weather forecasting. Furthermore, the emissivity models are included in two major radiative transfer model packages (CRTM and RTTOV). The emissivity models developed in this research are utilized in present operational NWP centers and by radiance data assimilation scientists around the world.

Regarding future prospects, it should be noted that there is a frontier area in microwave radiance assimilation, namely, the lower end of the microwave spectrum in the L-band range. Recently, measurements from L-band channels became available from the Soil Moisture and Ocean Salinity (SMOS) satellite. SMOS is a joint mission of the European Space Agency and the Centre National d'Etudes Spatiales. The objective of the SMOS satellite is to provide soil moisture and ocean salinity information. Microwave radiance from the earth's surface is measured with the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS). The Aquarius instrument onboard the SAC-D satellite also has the capability to measure the global sea surface salinity with an L-band 1.4 GHz channel. Modeling of the microwave radiance variation in terms of soil moisture and ocean salinity is an active research topic in these retrieval communities. The current realistic approach to using this information is in retrieval. In the radiative transfer calculation of L-band microwave radiance, a climatological value of ocean salinity is used for permittivity calculations in ocean emissivity models. Direct use of the L-band radiance data could be challenging and demand a realistic ocean salinity distribution as the first guess for data assimilation because the distribution of ocean surface salinity is not homogeneous and the density depends on the area. The effect of salinity should be included in ocean emissivity modeling for accurate simulation of microwave radiance.

Furthermore, although NWP models can provide ocean surface wind speeds and directions for the first guess in the retrieval process or in the radiative transfer calculation, the accuracy would not be sufficient to study the details of the wind speeds and directions (azimuth variations) and the effect of salinity on the L-band radiance data. In this study, simultaneous measurements of the radiance and surface wind vector from AMSR and SeaWinds on the ADEOS-II satellite were used for the development of ocean surface emissivity modeling. A future satellite mission with simultaneous measurements with a microwave radiometer and scatterometer is strongly recommended for understanding the mechanism of the atmosphere and ocean interaction.

Appendix

A. Definition of Precipitation Forecast Score

This appendix describes the precipitation forecast score used in this research. The verification of precipitation forecast is crucial for assessments on NWP system upgrades. In this research, traditional precipitation forecast scores, i.e., the Bias Score and the Threat Score, are used for verification. Precipitation events are counted based on a horizontal grid scale (e.g., 10 km) and a time interval (e.g., 3 hours) for forecasts and observations. The events are categorized with a contingency table (Table A.1). Precipitation data from ground-based radar, which are calibrated with rain gauges in Japan, are used as truth data (i.e., observed precipitation) for the precipitation verification.

Table A.1. Contingency table for the counts used in precipitation forecast verification statistics. The characters in parentheses indicate the forecast-observation combination of each case. For example, FO indicates forecasted and observed precipitation. XO indicates that no precipitation was forecasted but that precipitation was observed.

		Precipitation observed	
		Yes	No
Precipitation forecasted	Yes	Hits (FO)	False alarms (FX)
	No	Misses (XO)	No forecast (XX)

- Bias score (BI): The Bias Score is defined as the ratio of forecasted events to observed events. The score indicates a relative frequency of forecasted events compared with observed events.

$$BI = \frac{\text{forecasted events}}{\text{observed events}} = \frac{(FO + FX)}{(FO + XO)} \quad (A.1)$$

BI = 1 means unbiased; BI < 1 means under-forecasted; BI > 1 means over-forecasted.

- Threat Score (TS): The Threat Score is known as the critical success index. The score is the number of correct forecasts divided by the number of observed and/or forecasted events. A higher threat score indicates higher forecast skill in rare event prediction.

$$TS = \frac{\text{Hits}}{\text{all forecasted or all observed events}} = \frac{FO}{(FO + FX + XO)} \quad (A.2)$$

The TS varies from 0 to 1. TS = 0 means no skill. TS = 1 means a perfect forecast.

B. Definition of Relative Wind Direction

There are varying definitions used for the azimuthal wind and satellite angles. This appendix clarifies the situation, in particular the difference between FASTEM-5 and FASTEM-3, and it defines the angles used in the new relative wind direction (RWD) model function.

The satellite azimuth angle ϕ_s is defined using satellite location and observation location as Figure B.1(a). The satellite azimuth angle is used as input for the radiative transfer calculation (RTTOV). In RTTOV, microwave ocean emissivity module (FASTEM) calculates the emissivity for each channel (vertical, horizontal polarization, and the third and the fourth Stokes parameters). The input satellite azimuth angle ϕ_s is passed to the FASTEM. Azimuthal angle information used in FASTEM is calculated from the satellite azimuth angle ϕ_s and surface wind direction (10 m wind direction from NWP FG field). The definition of the azimuthal angle information is different between FASTEM-5 and FASTEM-3. FASTEM-4 azimuthal model function is the same as FASTEM-5 azimuthal function.

As shown in Figure B.1(a), the satellite azimuth angle ϕ_s and satellite azimuth view (looking) angle ϕ_v are related as follows:

$$\phi_v = \phi_s + 180. \quad (\text{B.1})$$

The angles are measured clockwise from north and describe a 0 to 360° range as shown in Figure B.1(a).

In FASTEM, the 10 m wind direction ϕ_w is defined as a direction towards which the wind is blowing. In meteorological convention, wind direction ϕ_m is defined as a direction from which the wind is blowing (Figure B.1(b)). The FASTEM wind direction ϕ_w and the meteorological wind direction ϕ_m are related as follows:

$$\phi_m = \phi_w + 180. \quad (\text{B.2})$$

The wind directions are measured clockwise from north and describe a 0 to 360° range.

FASTEM-5 uses RWD as input azimuthal angle information. RWD ϕ_r is defined as wind direction relative to the satellite azimuth angle. RWD is defined as follows:

$$\phi_r = \phi_w - \phi_s, \quad (\text{B.3})$$

where ϕ_w is FASTEM wind direction and ϕ_s is the satellite azimuth angle. The new RWD model function uses ϕ_r as input azimuthal angle information. The ranges of ϕ_w and ϕ_s are from 0 to 360°. RWD ϕ_r describes a 0 – 360° range. Using Eqs B.1, B.2 and B.3 it can be written as follows:

$$\phi_r = \phi_m - \phi_v. \quad (\text{B.4})$$

Equation B.4 indicates that RWD can be calculated from the meteorological wind direction and the satellite azimuth view angle. Figure B.1(c) illustrates the definition of RWD ϕ_r in a westerly wind case using the FASTEM wind direction ϕ_w and the satellite azimuth angle ϕ_s .

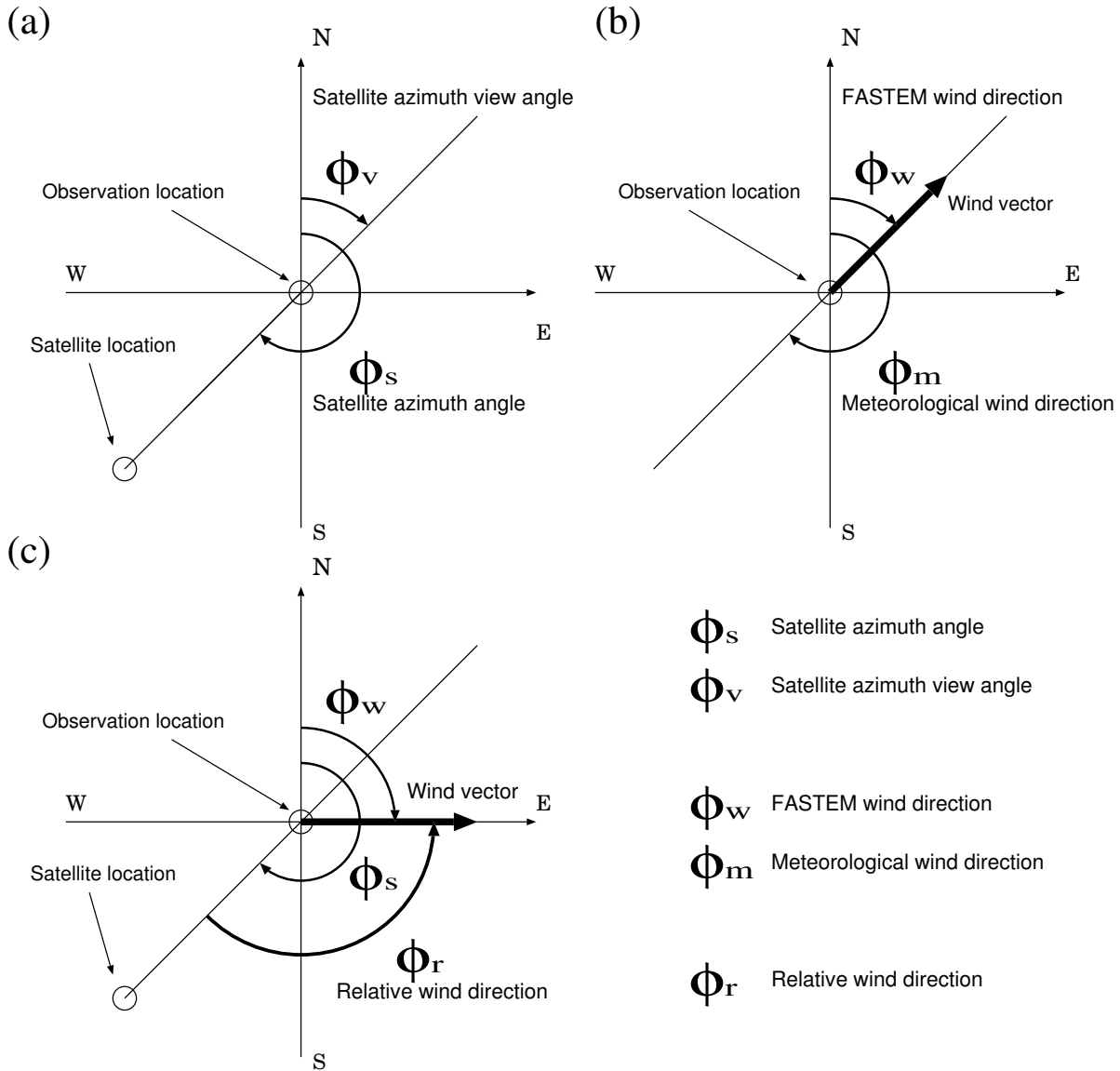


Figure B.1. Definitions of angles. (a) Satellite azimuth view angle and Satellite azimuth angle. (b) FASTEM wind direction and Meteorological wind direction. (c) Relative wind direction (westerly wind case). Wind vector is drawn as thick black arrow.

On the other hand, FASTEM-3 uses azimuth line of sight less the wind direction (Saunders et al., 2006) as the azimuthal angle information. The angle $\phi_{r(\text{FASTEM-3})}$ is defined as follows:

$$\phi_{r(\text{FASTEM-3})} = \phi_s - \phi_w. \quad (\text{B.5})$$

However, in the coding of RTTOV-10, actual input is defined as follows:

$$\phi_{r(\text{FASTEM-3})} = 180 - (\phi_w - \phi_s). \quad (\text{B.6})$$

By using Eqs B.1 and B.6 it can be written as follows:

$$\phi_{r(\text{FASTEM-3})} = \phi_v - \phi_w. \quad (\text{B.7})$$

Equation B.7 implies that FASTEM-3 azimuthal model function in RTTOV uses satellite azimuth view angle ϕ_v . This is an inconsistency in the present RTTOV coding and FASTEM-3 definition. In this study, the correct input for the azimuthal variation calculation for FASTEM-3 is used (results shown in Figure 5.7).

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