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Environmental Modeling Center
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TECHNICAL NOTE[1]

A NEURAL NETWORK-BASED FORWARD MODEL FOR DIRECT ASSIMILATION OF SSM/I BRIGHTNESS TEMPERATURES

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OPC CONTRIBUTIONS

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No. 2. Richardson, W. S., D. J. Schwab, Y. Y. Chao, and D. M. Wright, 1986: Lake Erie Wave Height Forecasts Generated by Empirical and Dynamical Methods -- Comparison and Verification. Technical Note, 23pp.

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No. 4. Rao, D. B., S. D. Steenrod, and B. V. Sanchez, 1987: A Method of Calculating the Total Flow from A Given Sea Surface Topography. NASA Technical Memorandum 87799., 19pp.

No. 5. Feit, D. M., 1986: Compendium of Marine Meteorological and Oceanographic Products of the Ocean Products Center. NOAA Technical Memorandum NWS NMC 68, 93pp.

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LIST OF ABBREVIATIONS

BT:	brightness temperature
C:	degrees Celsius
CC:	correlation coefficient
FM:	forward model, the same as GMF
FXX:	SSM/I instrument number XX
GHz:	10^9 cycles/second
GMF:	geophysical model function, the same as FM
H:	horizontal polarization
K:	degrees Kelvin
***L*:**	columnar liquid water
LIMA:	European oceanic weather ship
MIKE:	European oceanic weather ship
NCEP:	National Centers for Environmental Prediction
NDBC:	National Data Buoy Center
NN:	neural network
NRL:	Naval Research Laboratory
OMBNN3:	Ocean Modeling Branch Neural Network number 3 - SSM/I retrieval algorithm
OWS:	oceanic weather ship
PB:	physically-based
P&K	Petty and Katsaros (1992, 1994) - see References
SD:	standard deviation
SSM/I:	Special Sensor Microwave / Imager
SST:	sea surface temperature
TAO:	tropical atmosphere ocean
TOGA:	tropical ocean global atmosphere
V:	vertical polarization
***V*:**	columnar water vapor

1. INTRODUCTION

This report contains a description of a new neural network (NN) SSM/I forward model (FM) or geophysical model function (GMF) which generates SSM/I brightness temperatures (BTs) at five frequencies, 19GHz(V and H), 22GHz (V), and 37GHz(V and H) given the wind speed (*W* in m/s), columnar water vapor (*V* in mm), columnar liquid water (*L* in mm), and *SST* (in °C). This OMBFM1 (Ocean Modeling Branch Forward Model number 1) has been developed to be used for direct assimilation of SSM/I BTs into NCEP atmospheric forecast models.

There are two different approaches to developing GMF, a physically-based (PB) approach and an empirical approach. PB approaches use radiative transfer equations and various physical models to describe the air/sea interface and to derive the relationship between satellite BTs and atmospheric and oceanic parameters such as columnar liquid water, columnar water vapor, surface wind speed, and SST. Empirical FM derives relations between BTs and atmospheric and oceanic parameters from empirical data (e.g., collocation of satellite and buoy and/or radiosonde observations). Because PB approaches usually rely heavily on empirical parametrizations, using data similar to those used in the empirical approaches, the difference between PB and empirical approaches is not so great. For example, a SSM/I FM developed by Petty (1990) and Petty and Katsaros (1992, 1994) (P&K FM) uses only for the parametrization of atmospheric effects over 16,000 radiosonde/SSM/I matchups. As a result, PB FMs contain many empirical parameters. OMBFM1 which is a completely empirical FM contains approximately the same number of parameters (which correspond to the NN weights and biases). Several physically based GMFs for SSM/I BTs have been developed. Among them are P&K FM and Wentz (1992) FM. At the best of our knowledge, OMBFM1 is the first empirical FM for the SSM/I.

The purpose of this technical note is to document the development and validation of OMBFM1. In the Section 2, the architecture of the new GMF OMBFM1 is described. Section 3 describes the data sets which are used and the preprocessing of these data. Section 4 describes the training process. In Section 5 we perform detailed validation of the OMBFM1 using various criteria and matchups from different SSM/I instruments. Section 6 presents a sensitivity and error analysis, Section 7 summarizes our conclusions, and in the Appendix the FORTRAN program which implements OMBFM1 is presented[2].

2. THE ARCHITECTURE

The SSM/I FM orGMF represents the relationship between a vector of geophysical parameters $\boldsymbol{X}$ and a vector of satellite BTs $\boldsymbol{T}$

$$\boldsymbol{T} = F(\boldsymbol{X}) \quad (1)$$

where $\boldsymbol{T} = \{T19V, T19H, T22V, T37V, T37H\}$, $\boldsymbol{X} = \{W, V, L, SST\}$, and F is GMF or FM. The 85 GHz channel is not included in the output vector $\boldsymbol{T}$ in this first version of our empirical FM to simplify matters. For input vector $\boldsymbol{X}$, four geophysical parameters were included (wind speed, W, columnar water vapor, V, columnar liquid water L, and SST) which are the main parameters, determining satellite BTs, and which are used as inputs in the physically based FMs of P&K and Wentz.

The NN, OMBFM1, which implements eq. (1) has 4 inputs, $\{W, V, L, SST\}$, 5 standard BT outputs $\{T19V, T19H, T22V, T37V, T37H\}$, and 20 auxiliary outputs which produce derivatives of the outputs with respect to the inputs, or $\partial T_i / \partial X_j$. These derivatives constitute the Jacobian matrix $\boldsymbol{K}[\boldsymbol{X}] = \{\partial T_i / \partial X_j\}$ which emerges in the process of direct assimilation of the SSM/I BTs when the gradient of the SSM/I contribution to the cost function $\Psi_{SSM/I}$ is calculated. The cost function $\Psi_{SSM/I}$ can be written as (Parrish and Derber, 1992; Phalippou, 1996),

$$\Psi_{SSM/I} = \frac{1}{2}(\boldsymbol{F}(\boldsymbol{X}) - \boldsymbol{T^O})^T (\boldsymbol{O} + \boldsymbol{E})^{-1} (\boldsymbol{F}(\boldsymbol{X}) - \boldsymbol{T^O}) \quad (2)$$

where $\boldsymbol{T^O}$ is an observed SSM/I BT vector, $\boldsymbol{X} = \{W, V, L, SST\}$ is a state vector formed by the atmospheric and surface variables, $\boldsymbol{O}$ is the expected error covariance of the observations, $\boldsymbol{E}$ is the

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[2]The corresponding FORTRAN file is available upon request from Vladimir Krasnopolsky, e-mail address: wd21kv@sgi78.wwb.noaa.gov or general@dec01.wwb.noaa.gov, tel. 301-763-8133.

expected error covariance of the FM, and the superscript T denotes matrix transpose. The cost function gradient can be expressed as,

$$\nabla \Psi_{SSM/I} = K[X]^T \ (O + E)^{-1} \ (F(X) - T^O) \qquad (3)$$

Fig. 1 shows the OMBFM1 architecture. If auxiliary outputs are not taken into account, the architecture of OMBFM1 is mirror symmetric to the architecture of the NN retrieval algorithm OMBNN3 (Krasnopolsky et al., 1996) which, in some sense, may be considered as the inverse of OMBFM1.

The standard n-th output of a NN can be expressed as,

$$T_n = b_n + a_n \ \tanh\left(\sum_{j=1}^{k} \omega_{nj} \ z_j + \beta_n\right) \qquad (4)$$

where the ω_{nj} are the weights and β_n is the bias in the output layer, a_n and b_n are positive scaling factors, k is the number of hidden nodes, and z_j is the output of the j-th hidden node, which can be expressed as

$$z_j = \tanh\left(\sum_{i=1}^{m} \Omega_{ji} \ X_i + B_j\right) \qquad (5)$$

where Ω_{ji} are the weights and B_j are the biases in the hidden layer, and X_i are inputs to the NN. The elements of the Jacobian matrix, i.e. the derivatives $\partial T_i / \partial X_j$, which are used in the direct assimilation of BTs, are here calculated analytically given NN weights and biases without sacrificing accuracy as is the case in numerical differentiation,

$$\frac{\partial T_n}{\partial X_p} = \frac{1}{a_n} (a_n^2 + (T_n - b_n)^2) \sum_{j=1}^{k} (1 - z_j^2) \Omega_{pj} \omega_{jn} \qquad (6)$$

OMBFM1, therefore, provides not only the FM, F, but also the Jacobian matrix K for direct assimilation (2 - 3).

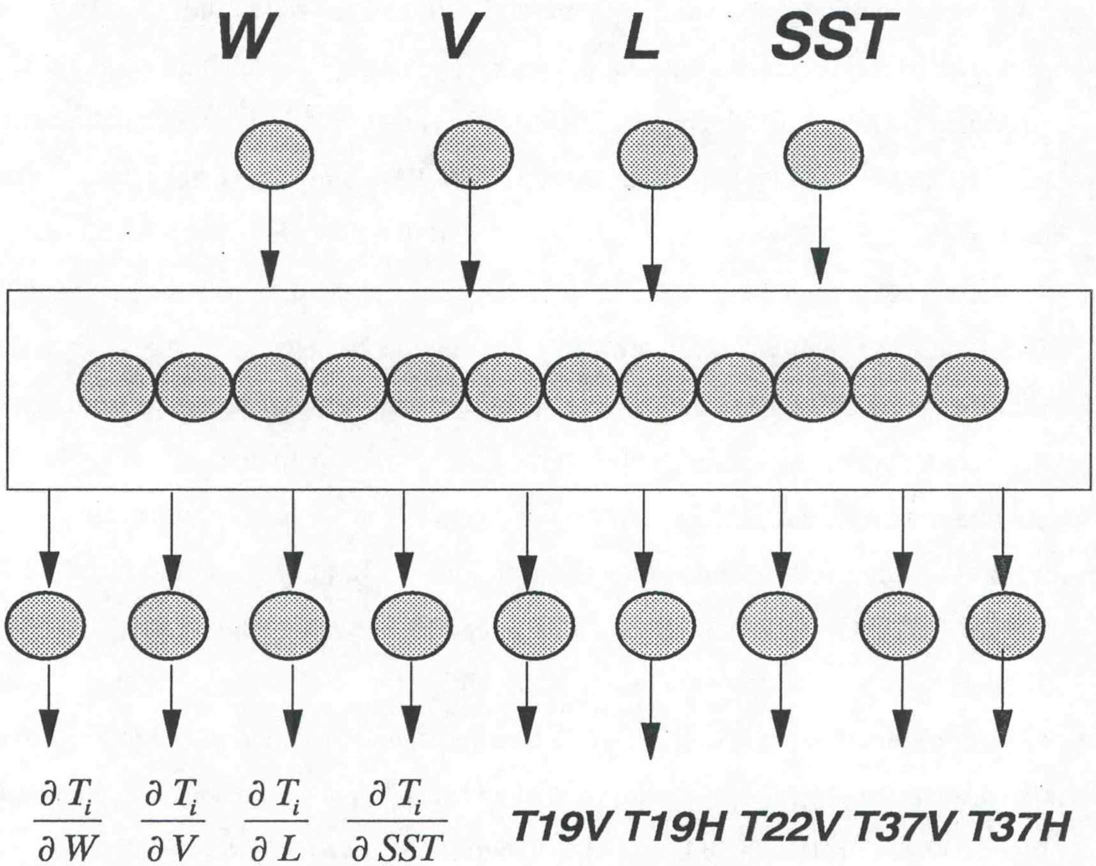


Fig. 1 NN SSM/I forward model OMBFM1.

Since these auxiliary outputs are not independent, we did not include them in the error function during training, hence, only the standard outputs $\boldsymbol{T}$ are involved in the training process. Including these additional outputs in the NN architecture simplifies the use of our NN GMF for direct assimilation.

3. THE DATA

For FM development and validation several data sources were used:

a. A raw SSMI/buoy matchup database, created by NRL. This database contains 12,013 F10/buoy matchups for the period 9/91 to 6/93 and 10,195 F11/buoy matchups for the period 12/91 to 6/93. NDBC buoys and TOGA-TAO buoys have been used in creating these matchups. We carefully quality-controlled these matchups extracted from the NRL database. More than 30 different criteria have been applied to both the buoy and the SSM/I data for quality control, including the removal of missing and noisy data. Daily locations for TOGA-TAO buoys have been corrected using information from the TAO Web Home page. As a result, subsets of 11,705 F10/buoy matchups and 9,948 F11/buoy matchups were extracted. As a second step, we selected matchups where the satellite data were collocated with the buoy data in space for $R_s \leq 15$ km and in time for $R_t \leq 15$ min. 7495 matchups were then selected for F10, and 6129 matchups for F11.

b. The F11/OWS matchups were collected by high latitude ocean weather ships (OWS) LIMA (430 matchups) and MIKE (639 matchups) and provided to us by D. Kilham (Bristol University). After quality control and applying a 15 km x 15 min collocation filter, 547 (243 MIKE + 304 LIMA) matchaps have been selected.

For all data, wind speeds have been adjusted to a height of 20 m. Some characteristics of the data are shown in Table 1. Clear and cloudy conditions are defined below and correspond to the retrieval flags given by Stogryn et al. (1994):

$$T37V - T\,37H > 50\ K \qquad \text{for clear conditions}$$

and

$$
\begin{aligned}
&T37V - T37H \le 50\ K && (7)\\
&T19V < T37V \\
&T19H \le 185\ K && \text{for cloudy conditions}\\
&T37H \le 210\ K
\end{aligned}
$$

Table 1. Statistics for data sets used for development and validation.

	Number of matchups			Mean W m/s	σ_w m/s	Max W m/s	Max W (Clear + Cloudy) m/s	Max W (Clear) m/s
	Total	**Clear**	**Cloudy**					
F10/Buoy	7495	5953	926	7.3	3.2	25.0	21.6	20.5
F11/Buoy	6633	5274	855	7.5	3.5	26.4	25.0	20.1
F11/LIMA	304	253	51	10.4	4.9	26.4	26.4	23.9
F11/MIKE	243	215	27	9.8	4.9	24.2	24.2	21.1

As can be seen from Table 1, most of the high wind speeds coincide with higher levels of moisture and cloudiness. Matchup data for F10 do not have buoy wind speeds higher than 21.6 m/s even under clear + cloudy conditions. Several high wind speed events in these data contain levels of liquid water which are so high that the atmosphere becomes opaque to microwave radiation. Only the F11 data contain high wind speed events under clear + cloudy conditions (up to 25 m/s). Thus, the F11 data provide the only choice for FM development. To further improve the coverage for high wind speeds, F11/buoy data have been supplemented with F11/LIMA and F11/MIKE data. These data have wind speeds up to 26.4 m/s and represent high latitudes (LIMA was located at ~ 57°N and MIKE at ~ 65°N). The resulting blended F11 matchup database has subsequently been separated into two statistically equivalent sets: one for training and a second for testing. The same training database has also been used for developing a new NN SSM/I retrieval algorithm OMBNN3 (Krasnopolsky et al., 1996).

4. TRAINING

As shown by Stogryn et al. (1994) and Krasnopolsky et al. (1994, 1995), NN retrieval algorithms can successfully operate under clear + cloudy, i.e., moist atmospheric conditions. Therefore, for training our NN FM we used all available matchups which corresponded to clear + cloudy conditions, according to Stogryn's retrieval flags (7). Statistics for clear conditions were then calculated by applying the trained NN to the clear portion of the matchup data.

Five SSM/I BTs *{T19V, T19H, T22V, T37V, T37H}* constitute the NN outputs. The input vector is composed of wind speed, *W*, and *SST* taken from the buoy portion of the F11 matchup database used for training, columnar water vapor, *V*, produced by the algorithm of Alishouse et al. (1990), and columnar liquid water, *L*, from the WG (Weng and Grody, 1994) algorithm. Back propagation was used to train the NN. After training, the algorithm was applied to the F11 test data. Table 2 shows wind speed statistics for clear +cloudy conditions and Table 3 - for clear conditions, for both training and test sets. In these tables each cell contains two numbers. The first number corresponds to the SSM/I observed BT and the second number to the FM generated BT.

Under both clear and clear + cloudy conditions, the OMBFM1 generated BTs compared with the SSM/I BTs have small biases, acceptable standard deviations for differences (SD), and high correlations (CC). Fig. 2 shows the observed and FM generated BT for all five channels. The FM also accurately reproduces not only the mean SSM/I BT for each channel but also its standard deviation, σ_T, and the range of variability (min and max BTs); therefore, the FM-generated BT distributions are properly centered and have proper widths (see Fig. 3). The horizontally polarized channels, 19H and 37H, have the highest SDs, ~2.5°K, under clear, and ~3°K under clear + cloudy conditions. For the vertically polarized channels, SDs are lower, ~1°K under clear, and ~1.5°K under clear + cloudy conditions. The differences in the statistics for training and test sets are not significant which shows that the NN was not overtrained. The difference between clear and clear + cloudy case is not large but significant.

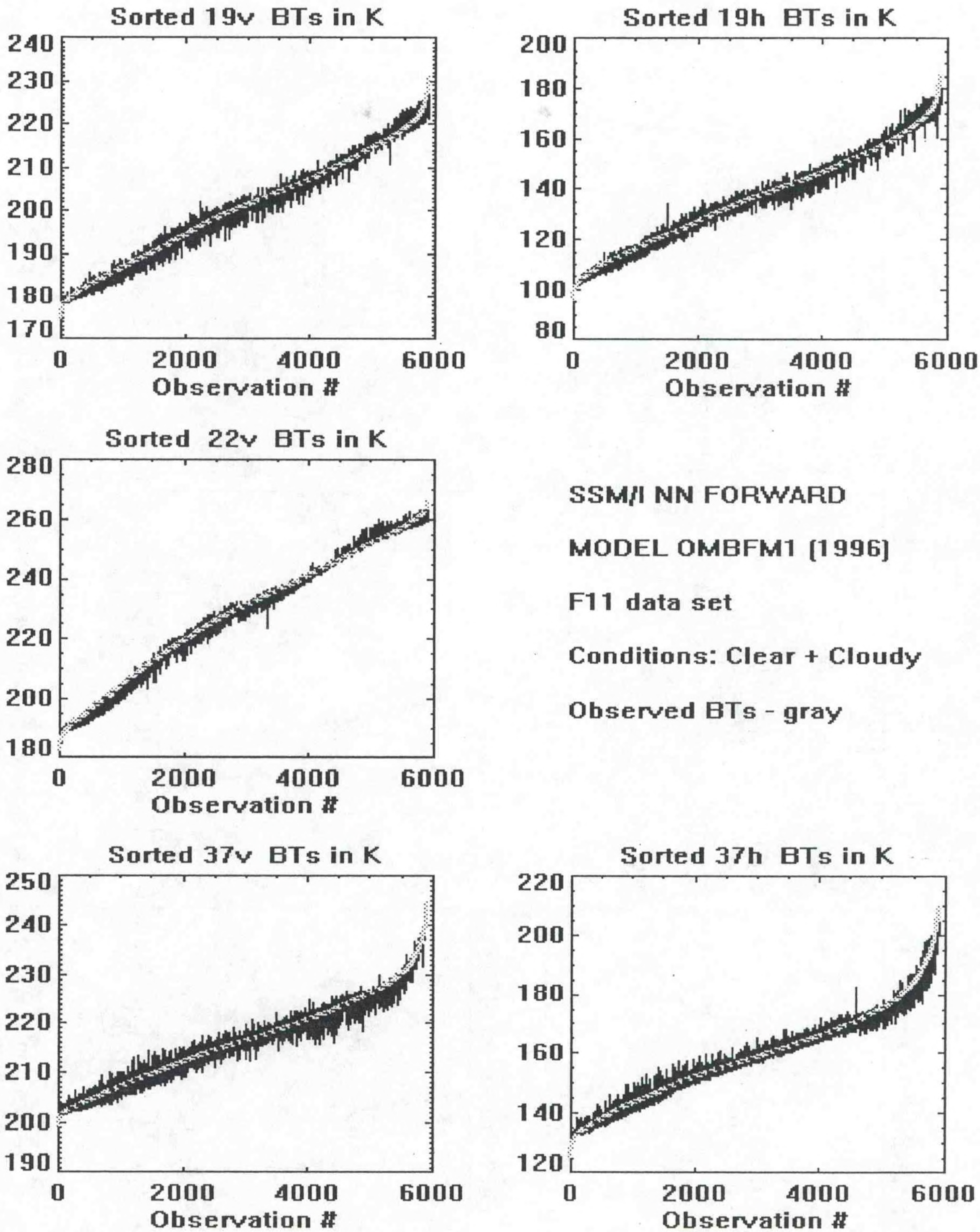
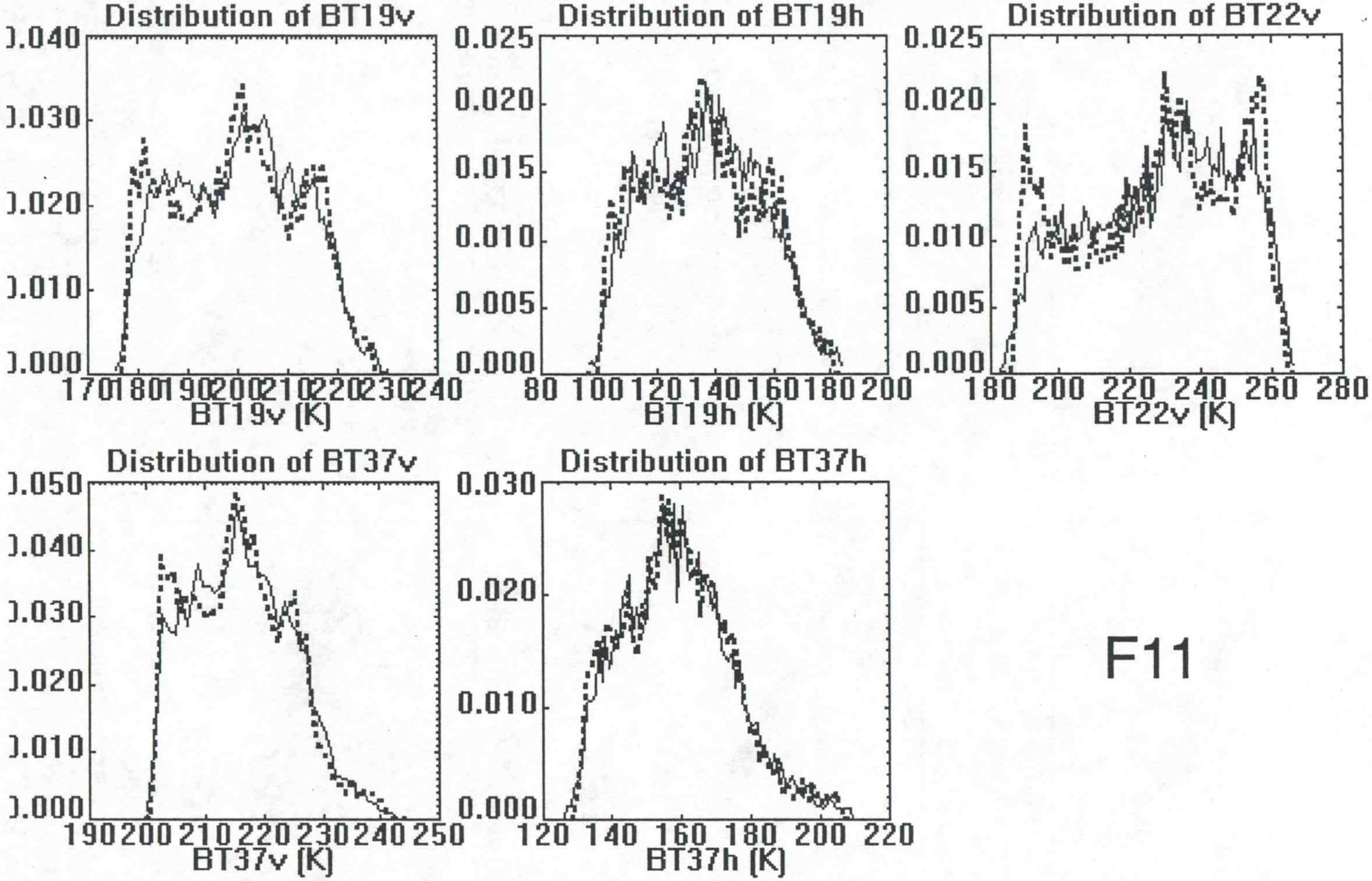


Fig. 2. Sorted BTs. Gray curves - observed BTs, black - BTs generated by OMBFM1.



F11

Fig. 3. Distribution of BTs. Solid line - observed BTs, doted line - BTs generated by OMBFM1.

Table 2. Training and test statistics for BTs under clear + cloudy conditions. Columns 3 - 6 show statistics for the BTs per se (σ_T denotes standard deviation), and columns 7 - 9 for the difference between SSM/I and OMBFM1-generated BTs. SD denotes standard deviation, and CC denotes correlation coefficient.

Data set	Chan nel	Min T (°K)	Max T (°K)	Mean T (°K)	σ_T (°K)	Bias (°K)	SD (°K)	CC
Trai ning N = 2950	T19V	175.0 / 178.0	230.8 / 227.6	200.6 / 200.6	12.3 / 12.2	0.0	1.4	0.99
	T19H	95.9 / 99.8	184.9 / 181.4	136.8 / 136.8	19.0 / 18.8	0.0	2.5	0.99
	T22V	182.5 / 187.4	265.8 / 264.9	228.6 / 228.6	20.8 / 20.7	0.0	1.2	1.00
	T37V	199.7 / 201.5	244.5 / 242.3	216.6 / 216.6	8.8 / 8.7	0.0	1.4	0.99
	T37H	125.5 / 129.1	209.3 / 207.0	159.4 / 159.4	15.9 / 15.5	0.0	3.1	0.98
Test N = 2972	T19V	175.7 / 177.8	230.3 / 227.7	200.4 / 200.4	12.3 / 12.2	0.0	1.4	0.99
	T19H	96.7 / 99.7	184.8 / 181.2	136.6 / 136.6	18.9 / 18.8	0.0	2.5	0.99
	T22V	183.7 / 187.2	266.3 / 264.6	228.3 / 228.3	20.9 / 20.8	0.0	1.0	1.00
	T37V	199.4 / 201.4	243.3 / 242.3	216.5 / 216.5	8.8 / 8.7	0.0	1.4	0.99
	T37H	126.6 / 129.2	209.8 / 207.1	159.1 / 159.1	15.9 / 15.5	0.0	3.1	0.98

Table 3. Training and test statistics for BTs under clear conditions. Columns 3 - 6 show statistics for the BTs per se (σ_T denotes standard deviation), and columns 7 - 9 for the difference between SSM/I and OMBFM1-generated BTs. SD denotes standard deviation, and CC denotes correlation coefficient.

Data set	Chan nel	Min T (°K)	Max T (°K)	Mean T (°K)	σ_T (°K)	Bias (°K)	SD (°K)	CC
Trai ning N = 2495	T19V	175.0 / 178.0	227.4 / 222.8	198.4 / 198.5	11.3 / 11.3	-0.1	1.2	0.99
	T19H	95.9 / 99.8	178.4 / 169.4	132.8 / 133.1	16.8 / 16.8	-0.2	2.1	0.99
	T22V	182.5 / 187.4	264.5 / 261.9	225.6 / 225.6	20.0 / 19.9	0.0	0.9	1.00
	T37V	199.7 / 201.5	237.3 / 235.9	214.5 / 214.5	7.3 / 7.2	-0.1	1.3	0.99
	T37H	125.5 / 129.1	183.3 / 200.0	154.9 / 155.1	15.9 / 15.5	-0.3	2.6	0.98
Test N = 2515	T19V	175.7 / 177.8	224.5 / 222.9	198.2 / 198.3	11.3 / 11.2	-0.1	1.2	0.99
	T19H	96.7 / 99.7	173.1 / 170.3	132.6 / 132.8	16.8 / 16.8	-0.2	2.0	0.99
	T22V	183.7 / 187.2	263.9 / 261.9	225.3 / 225.3	20.0 / 19.9	-0.1	0.9	1.00
	T37V	199.4 / 201.4	232.9 / 233.9	214.3 / 214.3	7.3 / 7.2	-0.1	1.2	0.99
	T37H	126.6 / 129.2	182.6 / 194.8	154.6 / 154.8	12.0 / 11.9	-0.3	2.6	0.98

5. VALIDATION

Here we use a newly-created database described in Section 3 for validation of OMBFM1 for F10 SSM/I instrument and for comparison with a PB FM. For comparison with the new OMBFM1 we have used a PB FM by P&K.

Table 4 shows total statistics for clear + cloudy case and Table 5 for clear conditions. Each table contains statistics for five BTs (T19V, T19H, T22V, T37V, and T37H) for F10 SSM/I, including minimum value, maximum value, mean value and standard deviation (σ_T), together with these statistics for BTs generated by OMBFM1 and PB FM. These tables also show some statistics (bias, standard deviation (SD), and correlation coefficient (CC)) for the differences between SSM/I and FM-generated BTs. Fig. 4 shows the observed and OMBFM1-generated BT for all five channels. Fig. 5 compares the OMBFM1-generated BT distributions with the observed BT distributions.

We now summarize the information contained in Tables 4 and 5:

Here, as in the case for the F11 instrument, for OMBFM1, horizontally-polarized channels, 19H and 37H, have the highest SDs: ~2.5°K under clear, and ~3.°K under clear + cloudy conditions. For the vertically polarized channels, SDs are lower: ≤1.5°K under clear, and ≤1.7°K under clear + cloudy conditions. The same trend can be observed for the PB FM, however, the absolute values of SDs for the PB FM are systematically higher for all weather conditions and for all channels considered.

Biases for OMBFM1 are also higher for horizontally-polarized channels (especially for 37H). For horizontally-polarized channels, OMBFM1 has a larger bias than the PB FM. These nonzero biases can be explained (at least partly) by the fact that OMBFM1 has been developed, using data from different satellite (F11). The wind direction signal may also contribute to this bias. Nonzero biases which OMBFM1 produces when applied to F10 data may be also due to slight calibrational errors and/or due to ellipticity of the F10 satellite orbit.

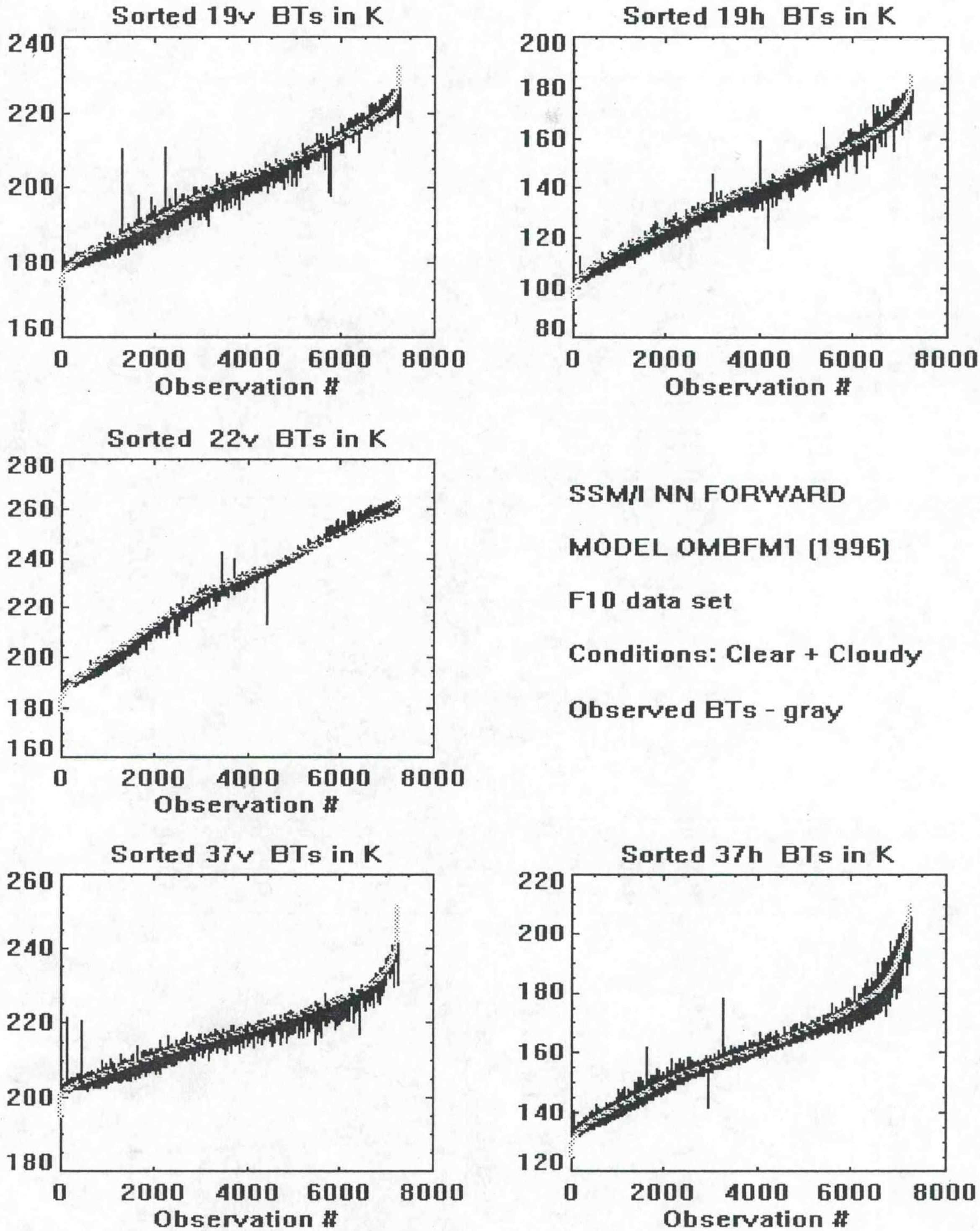
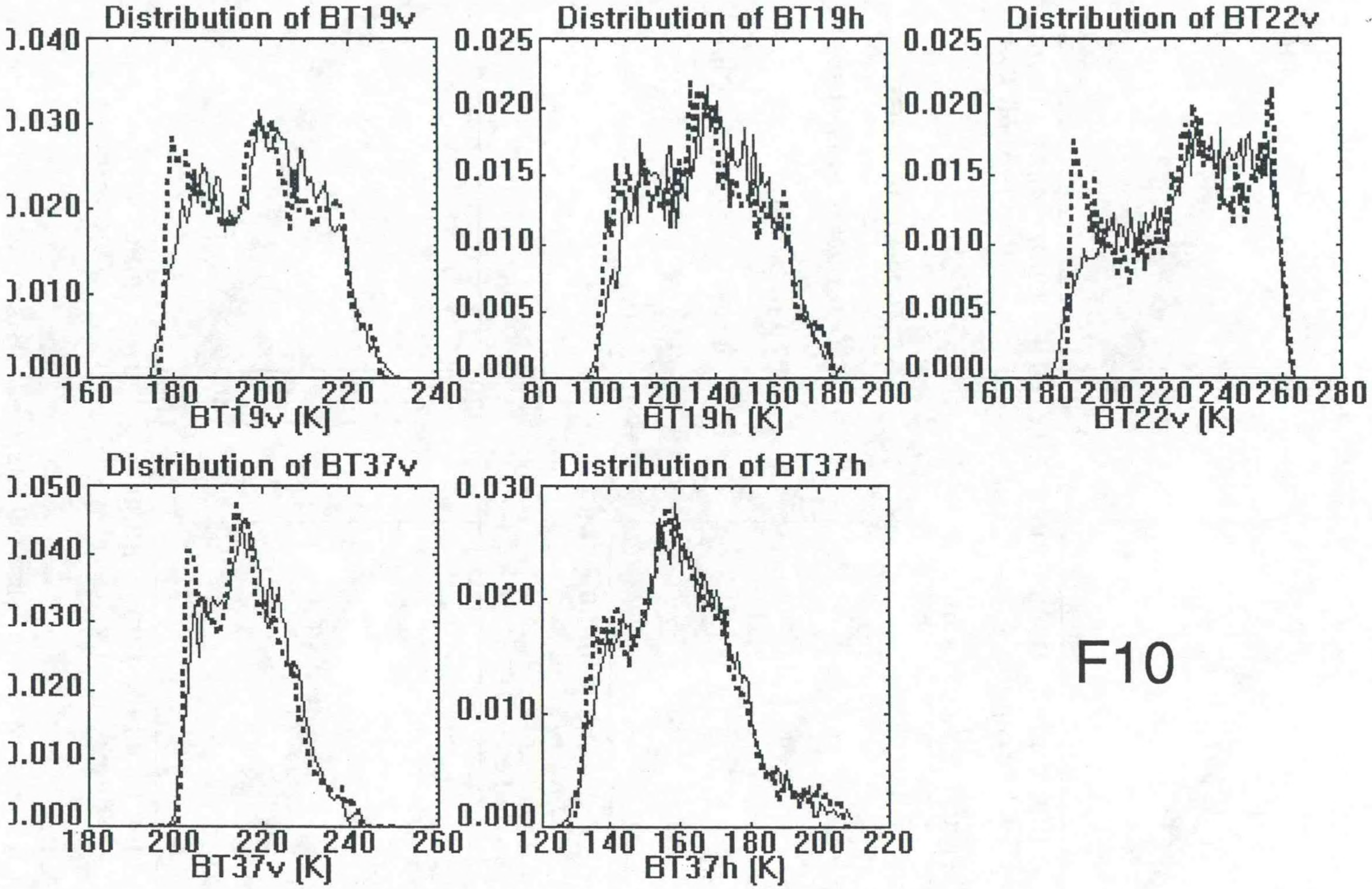


Fig. 4. Sorted BTs. Gray curves - observed BTs, black - BTs generated by OMBFM1.



F10

Fig. 5. Distribution of BTs. Solid line - observed BTs, dotted line - BTs generated by OMBFM1.

Table 4. Statistics for BTs under clear + cloudy conditions. Columns 3 - 6 show statistics for the BTs per se (σ_T denotes standard deviation), and columns 7 - 9 for the difference between F10 SSM/I and FM-generated BTs. SD denotes standard deviation for the difference, and CC denotes correlation coefficient.

Channel	**FM**	**Min T**	**Max T**	**Mean T**	σ_T	**Bias**	**SD**	**CC**
T19V	**F10 SSM/I**	173.5	232.0	200.6	12.5	N/A	N/A	N/A
	PB FM	176.3	225.8	199.8	11.9	0.8	2.1	0.99
	OMBFM1	177.6	227.3	199.9	12.1	0.7	1.7	0.99
T19H	**F10 SSM/I**	95.4	184.9	137.7	19.0	N/A	N/A	N/A
	PB FM	98.7	182.0	137.4	18.1	0.4	3.8	0.98
	OMBFM1	98.7	181.4	135.6	18.5	2.1	2.6	0.99
T22V	**F10 SSM/I**	178.8	264.9	227.6	20.9	N/A	N/A	N/A
	PB FM	183.9	260.1	227.2	20.2	0.4	2.1	0.99
	OMBFM1	186.1	264.2	227.2	20.7	0.4	1.2	1.00
T37V	**F10 SSM/I**	194.4	251.6	217.1	9.0	N/A	N/A	N/A
	PB FM	199.4	238.5	216.0	8.3	1.1	2.2	0.97
	OMBFM1	201.1	244.6	216.1	8.6	1.0	1.6	0.98
T37H	**F10 SSM/I**	124.9	209.4	160.0	15.8	N/A	N/A	N/A
	PB FM	129.6	204.9	159.5	14.4	0.5	4.8	0.95
	OMBFM1	128.7	211.3	158.4	15.2	1.5	3.1	0.98

Table 5. Statistics for BTs under clear conditions. Columns 3 - 6 show statistics for the BTs per se (σ_T denotes standard deviation), and columns 7 - 9 for the difference between F10 SSM/I and FM-generated BTs. SD denotes standard deviation for the difference, and CC denotes correlation coefficient.

Channel	**FM**	**Min T**	**Max T**	**Mean T**	σ_T	**Bias**	**SD**	**CC**
T19V	**F10 SSM/I**	173.5	228.6	198.4	11.5	N/A	N/A	N/A
	PB FM	176.3	221.9	197.9	11.2	0.5	1.8	0.98
	OMBFM1	177.3	221.1	197.9	11.1	0.5	1.5	0.99
T19H	**F10 SSM/I**	95.4	177.5	133.8	16.9	N/A	N/A	N/A
	PB FM	98.7	171.7	134.1	16.8	-0.3	2.9	0.99
	OMBFM1	98.7	169.8	131.9	16.5	1.9	2.3	0.99
T22V	**F10 SSM/I**	178.8	261.7	224.6	20.0	N/A	N/A	N/A
	PB FM	183.9	258.6	224.5	19.6	0.0	1.8	0.99
	OMBFM1	186.1	260.3	224.3	19.8	0.3	1.2	1.00
T37V	**F10 SSM/I**	194.4	251.6	214.9	7.5	N/A	N/A	N/A
	PB FM	199.4	235.9	214.2	7.3	0.8	1.9	0.97
	OMBFM1	201.1	244.6	214.1	7.1	0.9	1.5	0.98
T37H	**F10 SSM/I**	124.9	201.4	155.6	12.1	N/A	N/A	N/A
	PB FM	129.6	204.9	156.0	12.3	-0.4	3.7	0.95
	OMBFM1	128.7	210.5	154.4	11.9	1.2	2.8	0.97

6. SENSITIVITY AND ERROR ANALYSIS

Next, we estimate the Jacobian matrix $\boldsymbol{K}[X] = \{\partial T_i / \partial X_j\}$. The elements of this matrix reflect the sensitivity of the different BTs, T_i, to the different geophysical parameters X_j. To make possible a comparison between matrix elements corresponding to the different parameters X_j, new, unitless parameters $x_j = X_j / (max(X_j) - min(X_j))$ were introduced, and the normalized Jacobian matrix $\boldsymbol{K}[\boldsymbol{x}] = \{\partial T_i / \partial x_j\}$ was calculated, using both of our matchup data sets (F10 and F11). The results are presented in Fig. 6 (for F11) and Fig. 7 (for F10). Each figure has four panels which represent four rows of the normalized Jacobian matrix $\boldsymbol{K}[\boldsymbol{x}]$. Each panel shows five curves for one particular unitless geophysical parameter, x_j, and for all five BT channels, T_i. These curves represent maximum (solid line) and minimum (dotted line) values of the matrix elements, mean (dashed line) value of the matrix elements and an envelope of ± one standard deviation (dashed-dotted lines).

The figures show that, among the five considered channels, two channels, 19h and 37h, have the highest sensitivity to wind speed and columnar liquid water, and the 22v channel is primarily sensitive the columnar water vapor. All channels have a relatively low sensitivity to SST.

Errors in OMBFM1 are estimated as the difference between FM-generated and collocated SSM/I BTs in Sections 4 and 5. These errors, in addition to the errors of the FM per se, include other components such as collocation errors, radiometer noise, wind direction noise, etc. As mentioned above, there is a close connection between the FM OMBFM1 and the retrieval algorithm OMBNN3 which allows us to estimate true model errors for OMBFM1 and OMBNN3. OMBFM1 and OMBNN3 have a mirror symmetric architecture (the outputs of OMBNN3 are the inputs of OMBFM1 and vice versa), and they have been developed, using the same matchup data set; therefore, they may be considered as inverse to each other. Fig. 8 presents two different layouts which allow us to estimate true model errors for the OMBFM1+OMBNN3 in tandem, both in terms of (a) geophysical parameters and (b) BTs. In layout (a), the input vector $\boldsymbol{X}$ = $\{W,V,L,SST\}$ and the output vector $\boldsymbol{X'} = \{W',V',L',SST'\}$ are equal ($\boldsymbol{X'} - \boldsymbol{X} = 0$) if both models

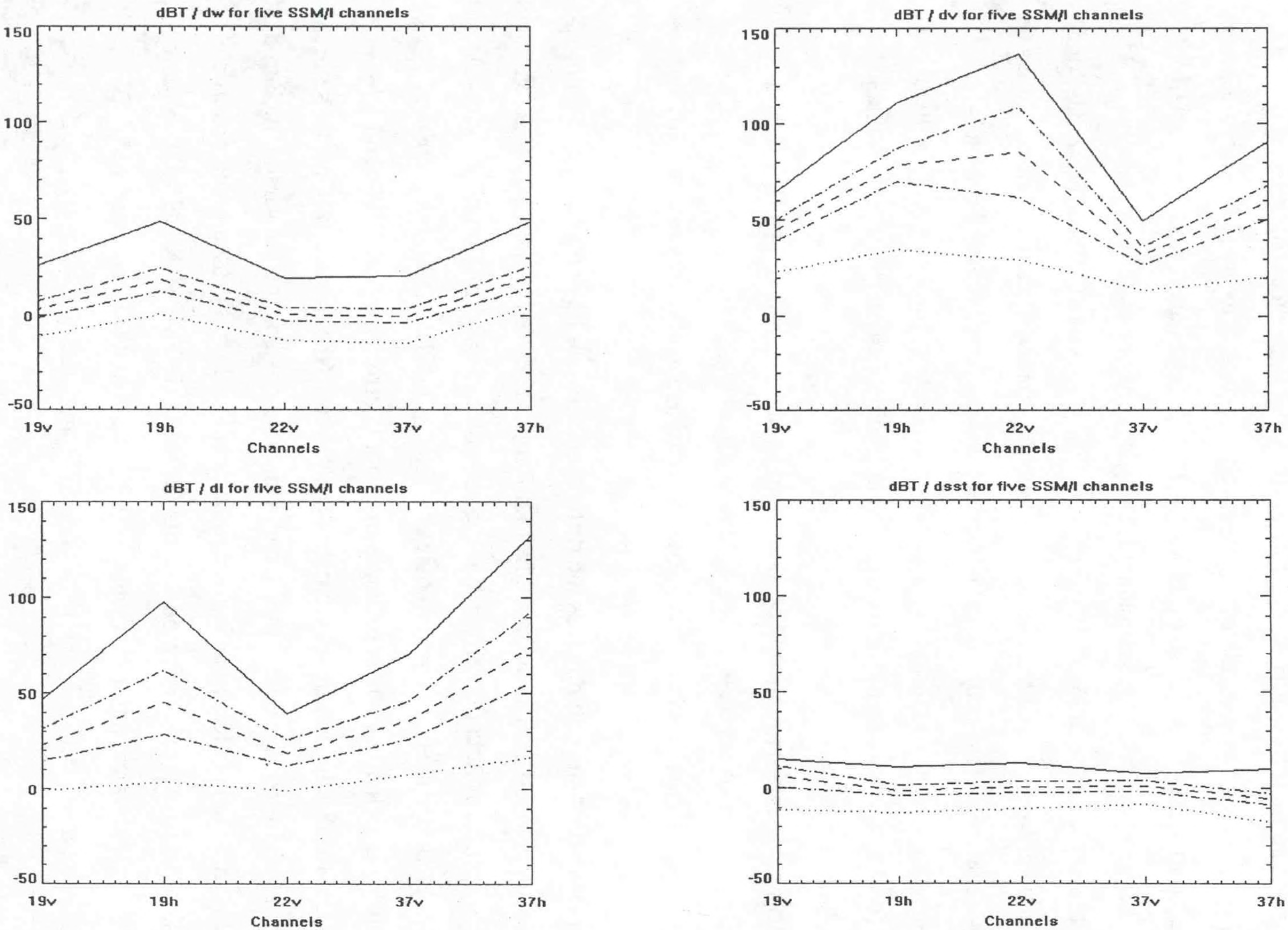


Fig. 6. Each panel shows five curves. Each curve represents the derivatives of all five F11 BT channels with respect to one particular unitless geophysical parameter (a row of the Jacobian matrix). These curves represent maximum (solid line) and minimum (dotted line) values of the matrix elements, mean (dashed line) value of the matrix element and an envelop of ± one standard deviation (dashed-dotted lines).

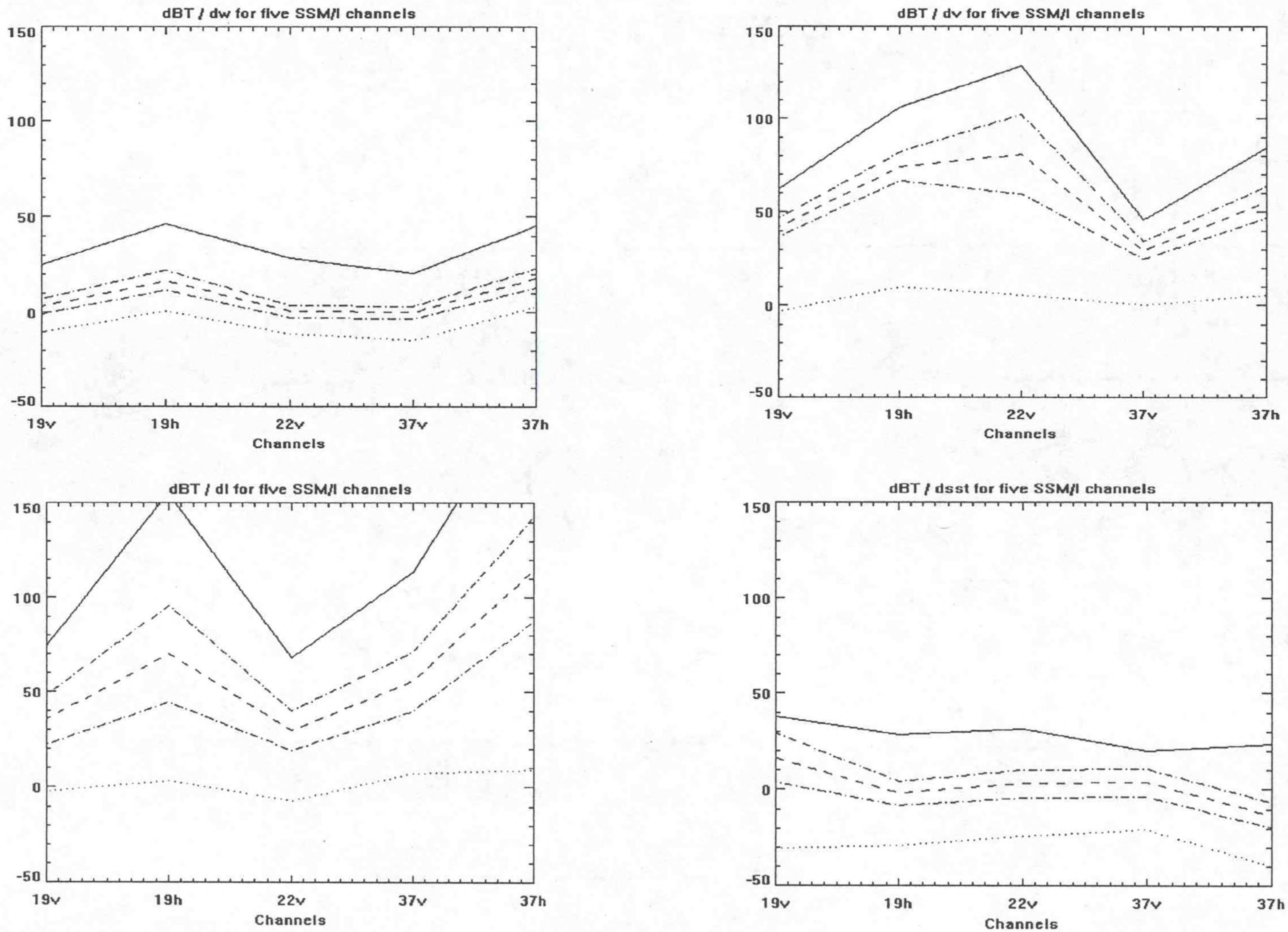


Fig. 7. Each panel shows five curves. Each curve represents the derivatives of all five F10 BT channels with respect to one particular unitless geophysical parameter (a row of the Jacobian matrix). These curves represent maximum (solid line) and minimum (dotted line) values of the matrix elements, mean (dashed line) value of the matrix element and an envelop of ± one standard deviation (dashed-dotted lines).

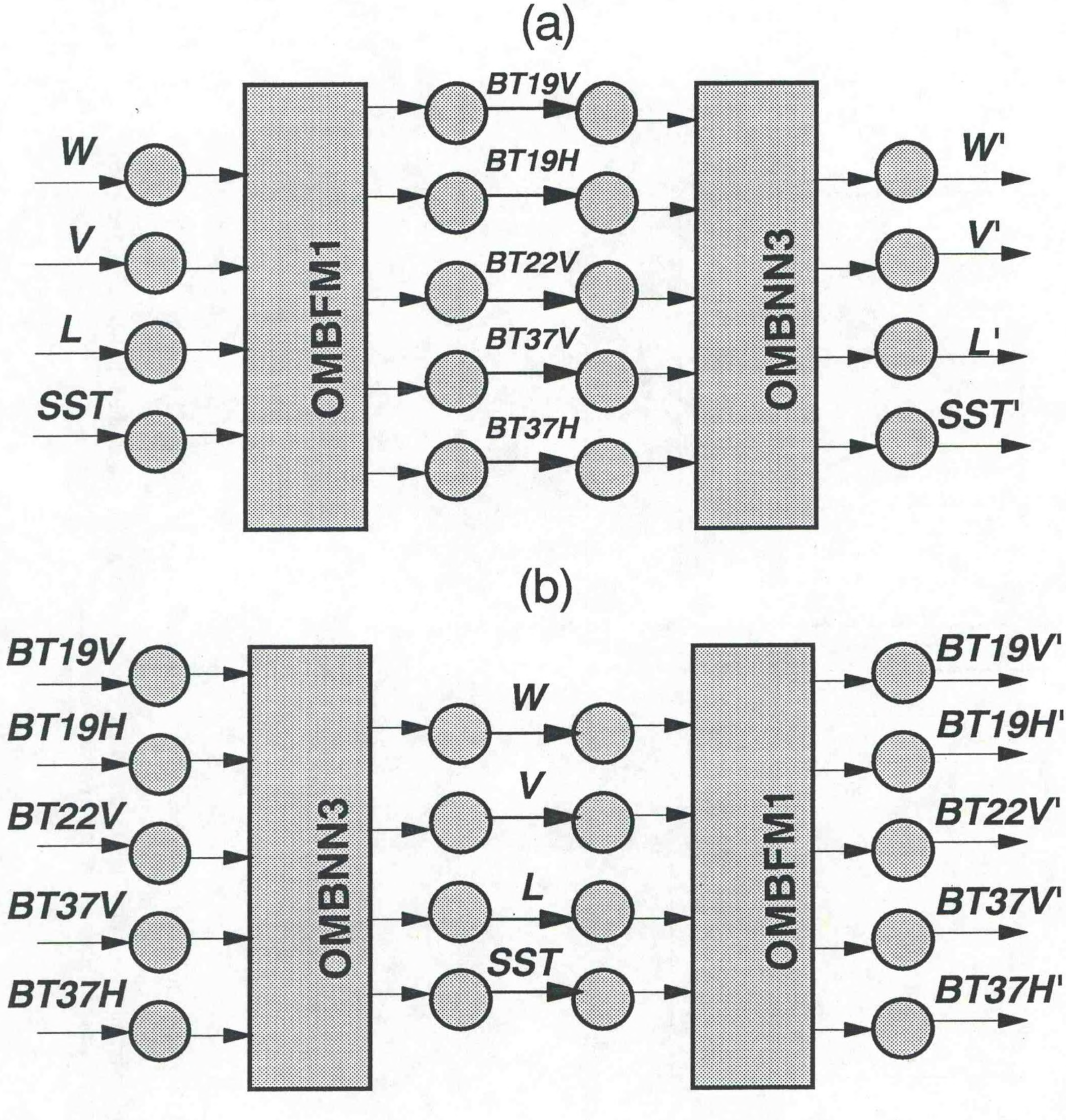


Fig. 8. Two different layouts (a) and (b) for evaluating internal model errors.

are perfect. The same is true about the layout (b) where $X = \{T19V, T19H, T22V, T37V, T37H\}$ and $X' = \{T19V', T19H', T22V', T37V', T37H'\}$. The departure of the difference $D = X - X'$ from zero gives an estimate for the true model errors for OMBFM1 and OMBNN3. Tables 6 presents an estimate of true model errors in terms of the various geophysical parameters (Fig. 8(a)). 5,923 vectors of geophysical parameters $X = \{W, V, L, SST\}$ from the F11 matchup data were used as inputs X for this estimate. Tables 7 presents an estimate of true model errors in terms of BTs (Fig. 8(b)). 5,923 F11 SSM/I BT vectors from out F11 matchup data set were used as inputs X to obtain this estimate. These estimated true model errors are important for comparing standard and direct assimilation of the SSM/I data into atmospheric models because the true model errors determine a lower bound for significant differences between the methods.

Table 6. True model errors in terms of geophysical parameters, columns 5 - 6 show mean error (bias) and standard deviation (SD), column 7 - correlation coefficient between X and X' (CC). Columns 2 - 4 show statistics for the geophysical parameters per se (X / X') and σ_X denotes standard deviation.

Parameter	Max X	Mean X	σ_X	Bias	SD	CC
W (m/s)	24.0/ 23.5	7.1/ 7.3	3.3 / 2.8	-0.2	1.0	0.96
V (mm)	64.4 / 58.6	31.1 / 30.8	15.6 / 16.1	0.3	1.2	1.0
L (mm)	0.38 / 0.34	0.034 /0.034	0.058 / 0.056	0.00	0.01	0.99
SST (°C)	31.4 / 30.1	19.5 / 20.5	9.2 / 7.9	-1.0	4.5	0.87

Table 7. True model errors in terms of BTs, columns 7 - 8 show mean error (bias) and standard deviation (SD), column 8 - correlation coefficient between X and X' (CC). Columns 3 - 6 show statistics for the BTs per se (X / X') and σ_X denotes standard deviation.

Channel	Min X (°K)	Max X (°K)	Mean X (°K)	σ_X (°K)	Bias (°K)	SD (°K)	CC
T19V	175.0 / 177.9	230.8/ 227.7	200.5/ 200.3	12.3 / 12.6	0.2	1.3	1.0
T19H	95.9 / 99.9	184.9 / 181.5	136.7 / 136.6	19.0 / 19.3	0.2	2.0	1.0
T22V	182.5 / 187.1	266.3 / 264.0	228.4 / 227.9	20.8 / 21.6	0.5	1.8	1.0
T37V	199.4 / 201.6	244.5 / 242.1	216.6 / 216.4	8.8 / 8.8	0.1	1.2	0.99
T37H	125.5 / 129.8	209.8 / 207.4	159.3 / 159.3	15.8 / 15.6	0.0	2.0	0.99

7. CONCLUSIONS

We have presented a new NN-based empirical SSM/I forward model called OMBFM1 which given the wind speed, columnar water vapor, columnar liquid water, and *SST*, generates five SSM/I BTs (T19V, T19H, T22V, T37V, and T37H) with an acceptable accuracy. Comparison with a PB FM (P&K FM), for all weather conditions permitted, shows that OMBFM1 is better than, or comparable with, PB FMs.

The OMBNN3 retrieval algorithm (Krasnopolsky et al., 1996) and OMBFM1 have mirror symmetry (outputs of OMBFM1 are inputs of OMBNN3 and vice versa). Also, they have been developed using the same matchup data; therefore, OMBNN3 may be considered as the inverse of OMBFM1. These two NNs, one which (OMBFM1) solves the SSM/I forward problem and another one (OMBNN3), which solves the SSM/I inverse problem, can be used to accurately compare direct and standard (i.e., inverse, via retrievals) assimilation of SSM/I BTs. True model errors which are important for this comparison are also estimated.

OMBFM1 generates the isotropic part of SSM/I BTs which does not depend on wind direction. The wind direction signal which is of order 2 - 3°K (Wentz, 1992) serves as a source of noise in this case. By including the wind directional component in our model, it may be possible to separate the wind directional signal and thus reduce bias and SD of the FM.

Acknowledgments

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APPENDIX

```
C*******************************************************************************
C
C Name: OMBFM1
C
C Language: FORTRAN77                    Type - SUBROUTINE
C
C Version: 1.0        Date: 09-17-96       Author: V. Krasnopolsky
C
C ---------------------------------------------------------------------------
C
   SUBROUTINE OMBFM1(X,Y,DYDX)
C
C ---------------------------------------------------------------------------
C
C Description:   This is NN forward model or geophysical model function for SSM/I.
C --------------  This NN was trained on blended F11 data set (SSMI/buoy matchups +
C              SSMI/OWS matchups 15km x 15 min) under Clear + Cloudy conditions
C              (Stogryn's retrieval flag) which approximatelly correspond to
C              L < 0.4 - 0.5 mm.  It is not recommended to apply OMBFM1 at
C              higher L.
C              OMBFM1 has been developed in EMC of NCEP, NOAA.
C              OMBFM1 means Ocean Modeling Branch (EMC, NCEP)Neural Network
C              Forward Model #1.  It generates SSM/I brightness temperatures (BT):
C              BT19V, BT19H, BT22V, BT37V and BT37H given the wind speed (W in m/s)
C              at the height 20. m, columnar water vapor (V in mm), columnar liquid
C              water (L in mm) and SST (in deg. C).  OMBFM1 also calculates
C              derivatives of BTs over W, V, L and SST.
C              The NN was trained using back-propagation algorithm.
C              OMBFM1 is described in OMB Technical Note No.  140  "A NEURAL NETWORK
C              FORWARD MODEL FOR SSM/I" by V. Krasnopolsky,
C
C               e-mail: wd21kv@sgi78.wwb.noaa.gov (V. Krasnopolsky)
C               Tel: 301-763-8133
C               Fax: 301-763-8545
C               address:
C               Environmental Modeling Center,
C               W/NMC21, Room 207,
C               5200 Auth Rd.
C               Camp Spring, MD 20746
C
C Description of training and test data set:
C -------------------------------------------------
C   The training set consist of 3460 matchups which were received from
C   two sources:
C   1.  3187 F11/SSMI/buoy matchups were filtered out from a preliminary
C      version of the new NRL database which was kindly provided by
C      G. Poe (NRL). Maximum available wind speed is 24 m/s.
C   2.  273 F11/SSMI/OWS matchups were filtered out from two datasets
C      collected by high latitude OWS LIMA and MIKE. These data sets were
C      kindly provided by D. Kilham (University of Bristol).Maximum
```

```
C        available wind speed is 26.4 m/s.
C     Satellite data are collocated with both buoy and OWS data in space
C     within 15 km and in time within 15 min.
C
C     The test data set has the same structure, the same number of matchups
C     and maximum buoy wind speed.
C
C ============================================================================
C
C SOME COMPARISON STATISTICS FOR F11 TEST SET:
C
C ============================================================================
C BTs statistics on test sets (CLEAR + CLOUDY conditions)
C D = BTsatell - BTmodel, SD - stand. dev.; CC - correlation coeff.:
C ---------------------------------------------------------------------------
C                 Min BT   Max BT   Mean BT   SD BT    Bias    SD D   CC (BTsat, BTmod)
C                 deg K    deg K    deg K     deg K    deg K   deg K
C----------------------------------------------------------------------------
C                       BT 19V
C ---------------------------------------------------------------------------
C SSM/I           175.7    230.3    200.4     12.3
C                                                      -0.006  1.42    0.993
C OMBFM1          177.8    227.7    200.4     12.2
C----------------------------------------------------------------------------
C                       BT 19H
C ---------------------------------------------------------------------------
C SSM/I            96.7    184.8    136.6     18.9
C                                                       0.02   2.49    0.991
C OMBFM1           99.7    181.2    136.6     18.8
C----------------------------------------------------------------------------
C                       BT 22V
C ---------------------------------------------------------------------------
C SSM/I           183.7    266.3    228.3     20.9
C                                                      -0.02   1.01    0.999
C OMBFM1          187.2    264.6    228.4     20.8
C----------------------------------------------------------------------------
C                       BT 37V
C ---------------------------------------------------------------------------
C SSM/I           199.4    243.3    216.5      8.8
C                                                       0.01   1.41    0.987
C OMBFM1          201.4    242.3    216.5      8.7
C----------------------------------------------------------------------------
C                       BT 37H
C ---------------------------------------------------------------------------
C SSM/I           126.6    209.8    159.2     15.9
C                                                       0.04   3.06    0.981
C OMBFM1          129.2    207.1    159.1     15.5
C----------------------------------------------------------------------------
C
C*************************************************************************
C
C CALLING FROM A FORTRAN PROGRAM:
```

```
C ==============================
C
C    REAL X(4),Y(5),DYDX(5,4)
C    Input X
C    CALL OMBFM1(X,Y,DYDX)
C
C***************************************************************************
C
      INTEGER HID,OUT
      PARAMETER (IN = 4, HID = 12, OUT = 5)
C
C Arguments:
C ---------
C INPUT:
C         X(1) = W - wind speed in m/s at the height 20 m
C         X(2) = V - columnar water vapor in mm
C         X(3) = L - columnar liquid water in mm
C         X(4) = SST in dec C
C
     DIMENSION X(IN)
C
C  OUTPUT:  BTs
C         Y(1) = T19V
C         Y(2) = T19H
C         Y(3) = T22V
C         Y(4) = T37V
C         Y(5) = T37H
C
C         DYDX(i,j) = dY(I)/dX(j); I = 1,..,OUT; j = 1,...,IN
C         derivatives of outputs (BTs) over inputs (W,V,L, and SST)
C
     DIMENSION Y(OUT),DYDX(OUT,IN)
C
C
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%
C
C Internal variables:
C ------------------
C
C       IN - NUMBER OF NN INPUTS
C
C       HID - NUMBER OF HIDDEN NODES
C
C       OUT - NUMBER OF OUTPUTS
C
C       W1 - INPUT WEIGHTS
C
C       W2 - HIDDEN WEIGHTS
C
C       B1 - HIDDEN BIASES
C
```

```
C     B2 - OUTPUT BIAS
C
      DIMENSION W1(IN,HID),W2(HID,OUT),B1(HID),B2(OUT)
C
C     A(OUT), B(OUT) - OUTPUT TRANSFORMATION COEFFICIENTS
C
C###############################################################################
C
      DIMENSION O1(IN),X2(HID),O2(HID),X3(OUT),O3(OUT),A(OUT),B(OUT)
C
      DATA ((W1(I,J),J = 1,HID),I = 1,IN)
     & /-0.0196909,0.000469835,-0.0355833,-0.0127482,-0.0452790,
     &-0.0552762,0.00711142,-0.0119401,0.0724249,-0.114600,0.0765579,
     &0.0462186,-0.0194260,0.0294191,0.0731808,0.0570750,0.0318723,
     &-0.0205220,0.0541103,0.0166078,0.0217549,0.0258847,-0.0109038,
     &0.0141959,1.65944,4.09372,-6.88147,2.56645,2.58955,0.344977,
     &0.168493,-2.63533,-0.149611,-4.18283,-2.86900,12.3661,0.0768516,
     &0.00399621,-0.0293703,-0.0148143,-0.0422821,-0.0180330,0.0101799,
     &0.00586564,-0.000881997,-0.00652825,-0.0279206,0.00598652/
      DATA ((W2(I,J),J = 1,OUT),I = 1,HID)
     & / 0.252935,0.0220921,0.0400708,0.131144,-0.0605750,0.356676,
     &0.484277,0.423199,0.504382,0.625677,0.137876,0.176632,-0.00785619,
     &0.215313,0.207205,0.389668,0.340875,0.839181,0.302863,0.132646,
     &0.420907,0.272828,0.380563,0.278892,0.137530,-0.236016,-0.439557,
     &-0.589991,0.118722,-0.205443,-0.245245,-0.265252,-0.512171,
     &0.0142726,0.0782267,0.523659,0.254154,0.859174,-0.111038,
     &-0.540984,0.378676,0.400412,0.395952,0.260658,0.267763,-0.241717,
     &-0.194556,-0.0865185,-0.311284,-0.197566,-0.0814274,-0.155645,
     &-0.221689,-0.217461,-0.192726,0.423372,0.559186,0.184526,
     &0.723609,0.771179/
      DATA (B1(I), I=1,HID)
     & /-1.10602,-2.46613,-0.316599,-0.133491,-0.572517,0.609209,
     &-1.39783,-0.0307912,-2.05501,1.61258,0.149796,0.134640/
      DATA (B2(I), I=1,OUT)
     & /-0.0687464,-0.229735,-0.330258,-0.134227,-0.121645/
      DATA (A(I), I=1,OUT)
     & /30.9911,49.4339,46.3106,24.9094,46.5617/
      DATA (B(I), I=1,OUT)
     & /202.919,140.435,224.174,222.080,167.402/
C
C
      DO I = 1,IN
        O1(I) = X(I)
      END DO
C
C - START NEURAL NETWORK
C
C - INITIALIZE X3
C
      DO K = 1,OUT
        X3(K) = 0.
C
```

```
C  - INITIALIZE X2
C
      DO I = 1, HID
        X2(I) = 0.
        DO J = 1,IN
          X2(I) = X2(I) + O1(J) * W1(J,I)
        END DO
        X2(I) = X2(I) + B1(I)
        O2(I) = TANH(X2(I))
        X3(K) = X3(K) + W2(I,K)*O2(I)
      END DO
C
      X3(K) = X3(K) + B2(K)
C
C --- CALCULATE O3
C
      O3(K) = TANH(X3(K))
      Y(K) = A(K) * O3(K) + B(K)
C
C ---  CALCULATE   DO/DI
C
      XY = A(K) * (1. - O3(K) * O3(K))
C
      DO J = 1, IN
       DUM = 0.
       DO I = 1,HID
         DUM = DUM + (1. - O2(I) * O2(I)) * W1(J,I) * W2(I,K)
       ENDDO
       DYDX(K,J) = DUM * XY
      ENDDO
C
    ENDDO
C
     RETURN
C
     END
C
C##########################################################################################
C
C-----  Table of results for different input values -------------------------
C
C **************************************************************************************
C
C      W      V     L    SST           T19V  T19H  T22V  T37V  T37H
C     m/s    mm   mm   deg C
C -------------------------------------------------------------------------------
C X = 1.00    .00    .00  30.00     Y = 178.61  97.66 184.60 200.58 126.64
C dY/dX(I,J) =
C 2.37309E-01 3.85254E-01 5.13367E+01 1.17725E-01
C 4.54153E-01 4.25065E-01 7.70307E+01 1.13801E-01
C 1.49061E-01 6.92852E-01 2.27107E+01 1.23185E-01
C 1.02201E-01 1.43323E-01 5.91959E+01 1.92349E-02
```

C 4.62823E-01 1.99935E-01 1.11496E+02 4.33219E-02
C X = 2.00 3.00 .02 29.00 Y = 181.14 101.32 187.75 202.53 130.45
C dY/dX(I,J) =
C 2.36866E-01 5.24410E-01 5.17766E+01 1.39355E-01
C 5.62532E-01 6.41944E-01 8.75325E+01 1.28987E-01
C 1.41522E-01 1.06147E+00 2.96765E+01 1.22633E-01
C 8.50025E-02 2.24985E-01 7.06831E+01 1.55608E-02
C 6.01967E-01 3.14649E-01 1.39219E+02 3.55185E-02
C X = 3.00 6.00 .04 28.00 Y = 183.94 105.75 192.25 204.81 135.04
C dY/dX(I,J) =
C 2.05300E-01 6.43850E-01 4.43325E+01 1.58234E-01
C 6.13504E-01 8.54149E-01 8.19592E+01 1.21440E-01
C 1.02980E-01 1.49795E+00 3.53503E+01 1.06249E-01
C 3.08847E-02 3.07352E-01 7.07926E+01 6.87313E-03
C 6.63168E-01 4.31464E-01 1.42717E+02 2.95098E-03
C X = 4.00 9.00 .06 27.00 Y = 186.81 110.59 198.05 207.20 139.97
C dY/dX(I,J) =
C 1.75850E-01 7.11125E-01 3.50755E+01 1.81901E-01
C 6.39864E-01 1.00808E+00 6.85713E+01 9.84067E-02
C 5.00972E-02 1.85926E+00 3.82021E+01 8.45822E-02
C-2.02004E-02 3.74042E-01 6.54828E+01 2.00984E-03
C 6.89770E-01 5.41648E-01 1.33196E+02-4.50487E-02
C X = 5.00 12.00 .08 26.00 Y = 189.55 115.54 204.58 209.61 145.09
C dY/dX(I,J) =
C 1.69819E-01 7.12018E-01 2.75895E+01 2.14498E-01
C 6.76820E-01 1.07312E+00 5.52238E+01 7.08256E-02
C 9.34339E-03 1.97875E+00 3.58797E+01 7.52251E-02
C-3.80606E-02 4.15299E-01 6.04903E+01 7.16400E-03
C 7.32072E-01 6.42954E-01 1.23736E+02-9.80330E-02
C X = 6.00 15.00 .10 25.00 Y = 192.07 120.41 210.92 212.03 150.48
C dY/dX(I,J) =
C 1.90149E-01 6.63909E-01 2.30210E+01 2.52212E-01
C 7.37039E-01 1.06436E+00 4.56503E+01 4.28093E-02
C-4.37277E-03 1.82852E+00 2.89088E+01 8.38383E-02
C-1.59821E-02 4.34304E-01 5.81120E+01 2.14253E-02
C 8.06888E-01 7.37724E-01 1.19804E+02-1.52013E-01
C X = 7.00 18.00 .12 24.00 Y = 194.35 125.16 216.40 214.49 156.27
C dY/dX(I,J) =
C 2.29700E-01 6.06464E-01 2.16886E+01 2.86045E-01
C 8.16657E-01 1.03458E+00 4.12716E+01 1.15279E-02
C 3.82158E-03 1.54579E+00 2.13608E+01 9.87339E-02
C 3.80338E-02 4.45466E-01 5.87354E+01 3.86537E-02
C 9.05191E-01 8.31695E-01 1.21773E+02-2.06748E-01
C X = 8.00 21.00 .14 23.00 Y = 196.52 129.96 220.93 217.08 162.59
C dY/dX(I,J) =
C 2.79800E-01 5.78233E-01 2.35827E+01 3.06962E-01
C 9.06246E-01 1.04065E+00 4.24591E+01-2.72687E-02
C 2.16445E-02 1.29498E+00 1.73767E+01 1.05065E-01
C 1.10926E-01 4.64831E-01 6.20322E+01 5.15346E-02
C 1.00504E+00 9.27578E-01 1.27906E+02-2.60561E-01
C X = 9.00 24.00 .16 22.00 Y = 198.79 135.08 224.86 219.91 169.48
C dY/dX(I,J) =

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C 3.33710E-01 6.00636E-01 2.82856E+01 3.08695E-01
C 9.94695E-01 1.11465E+00 4.86946E+01-7.48324E-02
C 4.15015E-02 1.16549E+00 1.87673E+01 9.57660E-02
C 1.89045E-01 5.01207E-01 6.71587E+01 5.46058E-02
C 1.07823E+00 1.01783E+00 1.35287E+02-3.07053E-01
C X = 10.00  27.00   .18  21.00    Y = 201.38 140.82 228.73 223.06 176.82
C dY/dX(I,J) =
C 3.85857E-01 6.74346E-01 3.48632E+01 2.88200E-01
C 1.06697E+00 1.25187E+00 5.83557E+01-1.27636E-01
C 6.13221E-02 1.16578E+00 2.50375E+01 7.19200E-02
C 2.58712E-01 5.51801E-01 7.25977E+01 4.57281E-02
C 1.09546E+00 1.08156E+00 1.39972E+02-3.35448E-01
C X = 11.00  30.00   .20  20.00    Y = 204.46 147.32 232.95 226.54 184.29
C dY/dX(I,J) =
C 4.29607E-01 7.80912E-01 4.17683E+01 2.46039E-01
C 1.10167E+00 1.41004E+00 6.84495E+01-1.76926E-01
C 8.08197E-02 1.25178E+00 3.40647E+01 3.99228E-02
C 3.06249E-01 6.01402E-01 7.61142E+01 2.67979E-02
C 1.03576E+00 1.08930E+00 1.37705E+02-3.35173E-01
C X = 12.00  33.00   .22  19.00    Y = 208.09 154.47 237.70 230.21 191.42
C dY/dX(I,J) =
C 4.55998E-01 8.85745E-01 4.68632E+01 1.87592E-01
C 1.07478E+00 1.51938E+00 7.48415E+01-2.10212E-01
C 9.83175E-02 1.35295E+00 4.26565E+01 9.15767E-03
C 3.20537E-01 6.26240E-01 7.52548E+01 3.60592E-03
C 8.99058E-01 1.01813E+00 1.25770E+02-3.02962E-01
C X =  13.00  36.00   .24  18.00    Y = 212.11 161.80 242.86 233.84 197.67
C dY/dX(I,J) =
C 4.55414E-01 9.46607E-01 4.79327E+01 1.23557E-01
C 9.72793E-01 1.51220E+00 7.37913E+01-2.16775E-01
C 1.09604E-01 1.39710E+00 4.74051E+01-1.09774E-02
C 2.98350E-01 6.05348E-01 6.85840E+01-1.63041E-02
C 7.11833E-01 8.70586E-01 1.05039E+02-2.47078E-01
C X = 14.00  39.00   .26  17.00    Y = 216.22 168.65 248.06 237.12 202.68
C dY/dX(I,J) =
C 4.22748E-01 9.32012E-01 4.38290E+01 6.69952E-02
C 8.07277E-01 1.36573E+00 6.44188E+01-1.95291E-01
C 1.09522E-01 1.33961E+00 4.61718E+01-1.53826E-02
C 2.47991E-01 5.35109E-01 5.69015E+01-2.75817E-02
C 5.15874E-01 6.79329E-01 8.00022E+01-1.83481E-01
C X = 15.00  42.00   .28  16.00    Y = 220.05 174.43 252.85 239.82 206.37
C dY/dX(I,J) =
C 3.62471E-01 8.40415E-01 3.54333E+01 2.71991E-02
C 6.13852E-01 1.12055E+00 4.96555E+01-1.55812E-01
C 9.56044E-02 1.18412E+00 3.93480E+01-6.03532E-03
C 1.85752E-01 4.33265E-01 4.30293E+01-2.97342E-02
C 3.46697E-01 4.88781E-01 5.61443E+01-1.26646E-01
C X = 16.00  45.00   .30  15.00    Y = 223.28 178.87 256.86 241.87 208.89
C dY/dX(I,J) =
C 2.87739E-01 7.00637E-01 2.52295E+01 5.55979E-03
C 4.32062E-01 8.49738E-01 3.41394E+01-1.12665E-01
C 7.03860E-02 9.74109E-01 2.94876E+01 1.00884E-02
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C 1.27054E-01 3.26495E-01 3.00676E+01-2.59824E-02
C 2.20125E-01 3.30833E-01 3.70410E+01-8.35042E-02
C X = 17.00  48.00    .32  14.00     Y = 225.81 182.05 259.99 243.33 210.54
C dY/dX(I,J) =
C 2.13325E-01 5.51118E-01 1.57287E+01-2.67440E-03
C 2.85766E-01 6.11464E-01 2.12532E+01-7.58852E-02
C 3.97897E-02 7.61004E-01 1.95089E+01 2.61070E-02
C 8.02388E-02 2.34564E-01 1.98261E+01-2.00991E-02
C 1.34482E-01 2.15783E-01 2.35454E+01-5.40659E-02
C X = 18.00  51.00    .34  13.00     Y = 227.68 184.21 262.28 244.32 211.59
C dY/dX(I,J) =
C 1.49083E-01 4.19144E-01 8.29854E+00-3.62650E-03
C 1.79762E-01 4.29212E-01 1.20849E+01-4.87807E-02
C 9.51094E-03 5.78260E-01 1.12241E+01 3.84254E-02
C 4.66818E-02 1.64750E-01 1.26112E+01-1.44570E-02
C 8.00721E-02 1.38751E-01 1.47739E+01-3.51560E-02
C X = 19.00  54.00    .36  12.00     Y = 229.01 185.65 263.91 244.99 212.25
C dY/dX(I,J) =
C 9.84777E-02 3.15247E-01 3.13413E+00-1.70959E-03
C 1.07692E-01 3.00811E-01 6.18910E+00-3.03789E-02
C-1.71497E-02 4.36887E-01 5.13572E+00 4.65260E-02
C 2.41021E-02 1.15554E-01 7.88597E+00-9.94220E-03
C 4.66119E-02 8.95601E-02 9.34367E+00-2.32988E-02
C X = 20.00  57.00    .38  11.00     Y = 229.94 186.61 265.04 245.43 212.68
C dY/dX(I,J) =
C 6.07143E-02 2.38591E-01-1.82898E-01 8.06099E-04
C 6.02458E-02 2.14015E-01 2.63466E+00-1.83504E-02
C-3.92383E-02 3.33823E-01 9.74516E-01 5.13583E-02
C 9.39026E-03 8.21694E-02 4.91718E+00-6.60653E-03
C 2.62420E-02 5.87364E-02 6.05557E+00-1.58477E-02
C X = 21.00  60.00    .40  10.00     Y = 230.59 187.24 265.81 245.73 212.96
C dY/dX(I,J) =
C 3.32953E-02 1.83792E-01-2.20123E+00 3.05640E-03
C 2.93254E-02 1.56123E-01 5.81004E-01-1.05436E-02
C-5.71486E-02 2.60912E-01-1.76412E+00 5.41119E-02
C-8.36665E-05 5.97763E-02 3.08942E+00-4.20977E-03
C 1.37859E-02 3.93901E-02 4.07207E+00-1.10722E-02
C X = 22.00  63.00    .42   9.00     Y = 231.04 187.68 266.34 245.93 213.14
C dY/dX(I,J) =
C 1.35771E-02 1.44995E-01-3.37781E+00 4.84688E-03
C 9.09720E-03 1.17325E-01-5.64995E-01-5.40431E-03
C-7.17433E-02 2.09928E-01-3.54319E+00 5.57153E-02
C-6.18486E-03 4.46675E-02 1.97334E+00-2.48260E-03
C 6.07595E-03 2.70602E-02 2.86674E+00-7.91763E-03
C X = 23.00  66.00    .44   8.00     Y = 231.36 187.97 266.69 246.08 213.27
C dY/dX(I,J) =
C-6.19673E-04 1.17412E-01-4.03181E+00 6.22683E-03
C-4.28990E-03 9.09087E-02-1.17699E+00-1.92271E-03
C-8.38825E-02 1.74321E-01-4.70400E+00 5.67661E-02
C-1.01334E-02 3.43008E-02 1.29458E+00-1.21079E-03
C 1.23446E-03 1.90134E-02 2.12486E+00-5.75846E-03
C X = 24.00  69.00    .46   7.00     Y = 231.59 188.18 266.93 246.18 213.36
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C dY/dX(I,J) =
C-1.09112E-02 9.75571E-02-4.36786E+00 7.30176E-03
C-1.32810E-02 7.25244E-02-1.47780E+00 5.27431E-04
C-9.42571E-02 1.49367E-01-5.47378E+00 5.76072E-02
C-1.27003E-02 2.70217E-02 8.84631E-01-2.43903E-04
C-1.84422E-03 1.36122E-02 1.66173E+00-4.22465E-03
C X = 25.00  72.00   .48   6.00     Y = 231.74 188.33 267.08 246.25 213.43
C dY/dX(I,J) =
C-1.84395E-02 8.30206E-02-4.51174E+00 8.16767E-03
C-1.94103E-02 5.94091E-02-1.59737E+00 2.32752E-03
C-1.03370E-01 1.31805E-01-5.99632E+00 5.84189E-02
C-1.43691E-02 2.17751E-02 6.41286E-01 5.17926E-04
C-3.81732E-03 9.87753E-03 1.36887E+00-3.09507E-03
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