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Current thrusts on TRMM and SSM/I based modeling studies on heavy rains and flooding episodes

T.N. KRISHNAMURTI, T.S.V. VIJAYA KUMAR, BRIAN MACKEY

NIHAT CUBUCKU, ROBERT S. ROSS

and

ROBERT F. ADLER*

Department of Meteorology, Florida State University, Tallahassee, Fl 32306-4520

*NASA, Goddard Space Flight Ctr, Mesoscale Atmosphere Proc Branch,

Atmospheres Lab, Code 912, Greenbelt, MD 20771

e mail : tnk@io.met.fsu.edu

सार – उष्णकटिबंधीय क्षेत्र में भारी वर्षा के लघु अवधि पूर्वानुमान के लिए फ्लोरिडा स्टेट यूनिवर्सिटी में हमारा अनुसंधान ग्रुप वास्तविक समय के आधार पर बहुविश्लेषण/बहुनिदर्श पद्धति का उपयोग कर रहा है। सुपरएंसेम्बल पूर्वानुमानों की व्याख्या करने से संबंधित पद्धति विज्ञान इस विषय पर हमारे हाल के प्रकाशनों का अनुसरण करता है। वर्षण के बहुविश्लेषण/बहुनिदर्श सुपरएंसेम्बल पूर्वानुमान करने में हाल में हुए सुधारों से मेंबर मॉडलों की तुलना में इसमें अधिक कुशलता आई है। इस पद्धति से भारी वर्षा के कारण आने वाली क्षेत्रीय बाढ़ के बारे में कुछ उपयोगी दिशानिर्देश देना संभव हो सकेगा। ये 1 से 5 दिनों के पूर्वानुमान हैं जिसमें इकिवटेबल थ्रेट स्कोर्स प्रतिदिन 25 मि. मि. से अधिक कुल वर्षा सबसे अधिक बेहतर मेंबर मॉडल की तुलना में सुपरएंसेम्बल के लिए दोगुने से तिगुने तक बेहतर रहा। इस अध्ययन में, बहुत से भूमंडलीय प्रचालनात्मक केंद्रों के बहुनिदर्शों और बहुविश्लेषण घटक, जो टी.आर.एम.एम. और एस.एस.एम./आई. डाटा सेटों और बहुत से वर्षा दर एलगोरिथ्म का उपयोग करने वाले एफ.एस.यू भूमंडलीय स्पैक्ट्रल निदर्श पर आधारित है, का उपयोग करके पूर्वानुमान भी किया गया है। इन विभिन्न वर्षा दर एलगोरिथ्म के उपयोग से भैतिक इनीशिचलाइजेशन में विश्लेषणों में भिन्नता आती है जिसके फलस्वरूप अपसरण, उष्णन, नमी और वर्षा दर की व्याख्या में सुस्पष्ट भिन्नता उत्पन्न होती है। 5 भूमंडलीय प्रचालनात्मक निदर्श और भिन्न वर्षा दर एलगोरिथ्म द्वारा आरंभ किए गए एफ.एस.यू निदर्शों से लिए गए बहु विश्लेषण पूर्वानुमान से संबंधित 6 निदर्शों को मिलाकर कुल 11 निदर्श बहु विश्लेषण/बहु निदर्श तंत्र में लगाए गए हैं। सूक्ष्मतरंग उपकरणों द्वारा प्राप्त किए गए टी.आर.एम.एम और एस.एस.एम./आई वर्षा के डाटा सेट वर्षा के पूर्वानुमान में हुए इन अभूतपूर्व सुधारों की कुँजी है। निदर्शों के सांख्यिकीय बायसों का निर्धारण इन पूर्वानुमानों के बहुरैखिक समाश्रयण द्वारा किया गया है जो नासा गोड्डार्ड में हाल में विकसित किए गए वर्षा दर एलगोरिथ्म का उपयोग करने वाले टी.आर.एम.एम. और एस.एस.एम./आई आँकड़ा सेट पर आधारित हैं। हमने उन आकलनों की श्रृंखला के बारें में भी बताया है जो भारी वर्षा की घटना के "वॉक थ्रू" को दिखाते हैं। इस अध्ययन में विशेष रूप से भारत, बंगलादेश, संयुक्त राज्य अमरीका, मोजाम्बिक / मेडागास्कर और फिलीपीन्स में आई हाल की बाढ़ की घटनाओं के बारे में बताया गया है। इसके परिणाम सबसे बेहतर और निम्नतम निष्पादन वाले निदर्श, एनसेम्बल औसत और नियंत्रण प्रयोग (जो किसी भी टी.आर.एम.एम. अथवा एस.एस.एम./आई. डाटा सेटों का उपयोग नही करते हैं) के मुकाबले सुपरएंसेम्बल के निष्पादन की तुलना के हैं। वर्तमान में उपलब्ध अच्छे निदर्शों के मुकाबले इन परिणामों के अच्छे नतीजे निकले हैं।

ABSTRACT. Our research group at the Florida State University has been using a multianalysis/multimodel approach on real time for the short-range prediction of heavy rains over the tropical belt. The methodology for the construction of the superensemble forecasts follows our recent publications on this topic. Recent improvements in multianalysis/multimodel superensemble forecasts of precipitation have led to much higher skills compared to the member models. This suggested that some useful guidance for regional floods arising from heavy rains might be possible from this approach. These are 1 to 5 day forecasts where the equitable threat scores for rainfall totals in excess of 25 mm/day have been two to three times better for the superensemble compared to the best member model. This study includes forecasts using multimodels from a number of global operational centers and a multianalysis component, which is based on the FSU global spectral model that utilizes TRMM and SSM/I data sets and a number of rain rate algorithms. The differences in the analyses arise from the use of these different rain rate algorithms within physical initialization, which in turn, produces distinct differences among divergence, heating, moisture, and rain rate descriptions. A total of 11 models, of which 5 represent global operational models and 6 represent multianalysis forecasts from the FSU model

initialized by different rain rate algorithms, are embedded in the multianalysis/multimodel system studied here. The TRMM and the SSM/I rainfall data sets derived from microwave instruments are key to these marked improvements of rainfall forecasts. The statistical biases of the models are determined from a multiple linear regression of these forecasts against a 'best' rainfall analysis field, which is based on a TRMM and SSM/I data set that utilizes rain rate algorithms recently developed at NASA Goddard. We also display a sequence of computations that illustrate a "walk-through" of a heavy rain episode. This study specifically deals with recent flood episodes over India, Bangladesh, the United States of America, Mozambique/Madagascar and the Philippines. These results compare the performance of the superensemble against the best and lowest performing model, the ensemble mean and the control experiment (that does not use any TRMM or SSM/I data sets). Overall these results show great promise over the current best models.

1. Introduction

This paper is a sequel to a recent study on precipitation forecasts using a multimodel superensemble (Krishnamurti *et al*., 2001). Here the emphasis is placed on recent flood episodes and the potential use of the multimodel superensemble for the prediction of such events. In our previous study, we utilized the real time global forecasts of precipitation (out to day 6) from a suite of eleven models. Five of these were operational global weather forecast models from NCEP (US), JMA (Japan), NOGAPS (U.S. Navy), BMRC (Australia), and RPN (Canada). A list of acronyms is presented in Table 1. The other six daily forecasts came from the FSU global spectral model (Krishnamurti *et al*., 1998) where the initial states were derived from physical initialization, following Krishnamurti *et al*., (1991). The success of this work depended on the use of the TRMM data sets. The NASA TRMM satellite has been providing microwave radiance data sets since its launch in 1998. To those data sets we have added the microwave radiance data sets from as many as four U.S. Air force DMSP satellites (F11, F13, F14 and F15). The OLR data sets from NOAA polar orbiting satellites were also incorporated in the present study in order to derive a first guess rainfall estimate over the globe using the Arkin algorithm (Xie and Arkin, 1996). The rain rates along the swaths of the TRMM and DMSP satellites are derived daily using microwave radiance-based rain rate algorithms developed by Kummerow *et al*., (1996, 2000), Ferraro and Marks (1995), Olson (1996) and Turk *et al*., (2001). These five different rain rate data sets are assimilated into the FSU global model using physical initialization. This procedure (Krishnamurti *et al*., 1991) provides a means to incorporate the six methods for computing rain rates (*via* these diverse algorithms). Within the FSU data assimilation, physical initialization provides a spin-up at the initial time for the divergence, diabatic heating, surface pressure tendencies, moisture profiles and the model based precipitation fields. This procedure results in five different analyses over the global belt and constitutes the multianalysis component of our study. All of these multianalysis components are used within the FSU global spectral model, and the details on this real time

TABLE 1

List of Acronyms

TRMM	Tropical Rainfall Measuring Mission
SSM/I	Special Sensor Microwave Instrument
NASA	National Aeronautical Space Agency
NCEP	National Center for Environmental Prediction
JMA	Japan Meteorological Agency
NOGAPS	Navy Operational Global Atmospheric Prediction System
BMRC	Bureau of Meteorology Research Center
RPN	Recherché en Prévision Numérique
DMSP	Defense Meteorological Satellite Program
OLR	Outgoing Longwave Radiation
NOAA	National Oceanic and Atmospheric Administration
FSU	Florida State University
FSUGSM	Florida State University Global Spectral Model
TMI	TRMM Microwave Imager
ITCZ	Inter Tropical Convergence Zone
FEMA	Federal Emergency Management Agency

precipitation forecast effort are described in Krishnamurti *et al*., (2001). Thus, this total of 11 models includes a mix of non-FSU multimodels and multianalysis (tied to the FSU model). This array of model forecast runs has been incorporated at FSU on a daily real-time basis since 1999.

2. The superensemble approach

The superensemble approach is a recent contribution to the general area of weather and climate forecasting developed at FSU and is discussed in detail in a series of publications by Krishnamurti *et al*., (1999, 2000a, 2000b and 2001). The superensemble methodology yields forecasts with considerable reduction in forecast error compared to the error in the member models, the 'bias-removed' ensemble averaged forecast and the ensemble mean. This technique entails the division of a time line into two parts. One part is a 'training' phase where forecasts by a set of member models are compared to observed fields to develop a least squares fit of the

forecasts to the observations.   Specifically, the observed anomalies are fit to the member model forecasts according to the methodology described in Krishnamurti *et al*., (2000a). Regression coefficients are determined using Gauss-Jordan elimination technique by minimizing the summed squared error integrated over the training period. A fit of this sort is performed for all model variables and at all model grid points for which observations are available and typically yields about 10-million regression parameters. These may be thought of as bias correction weights. The second time line part is composed of genuine model predictions combined according to the weights determined during the training period to obtain the superensemble forecast. This forecast differs from the biased-removed ensemble mean or simple ensemble mean forecasts. The difference comes in the form of weighting the multimodels based on their past performance. The construction of the superensemble can be considered a post-processing algorithm of multimodel forecasts, but it is still a viable forecast product that is being prepared experimentally in real time at FSU. The precipitation superensemble has also been implemented in real time and is providing 5-day forecasts every day on an experimental basis.
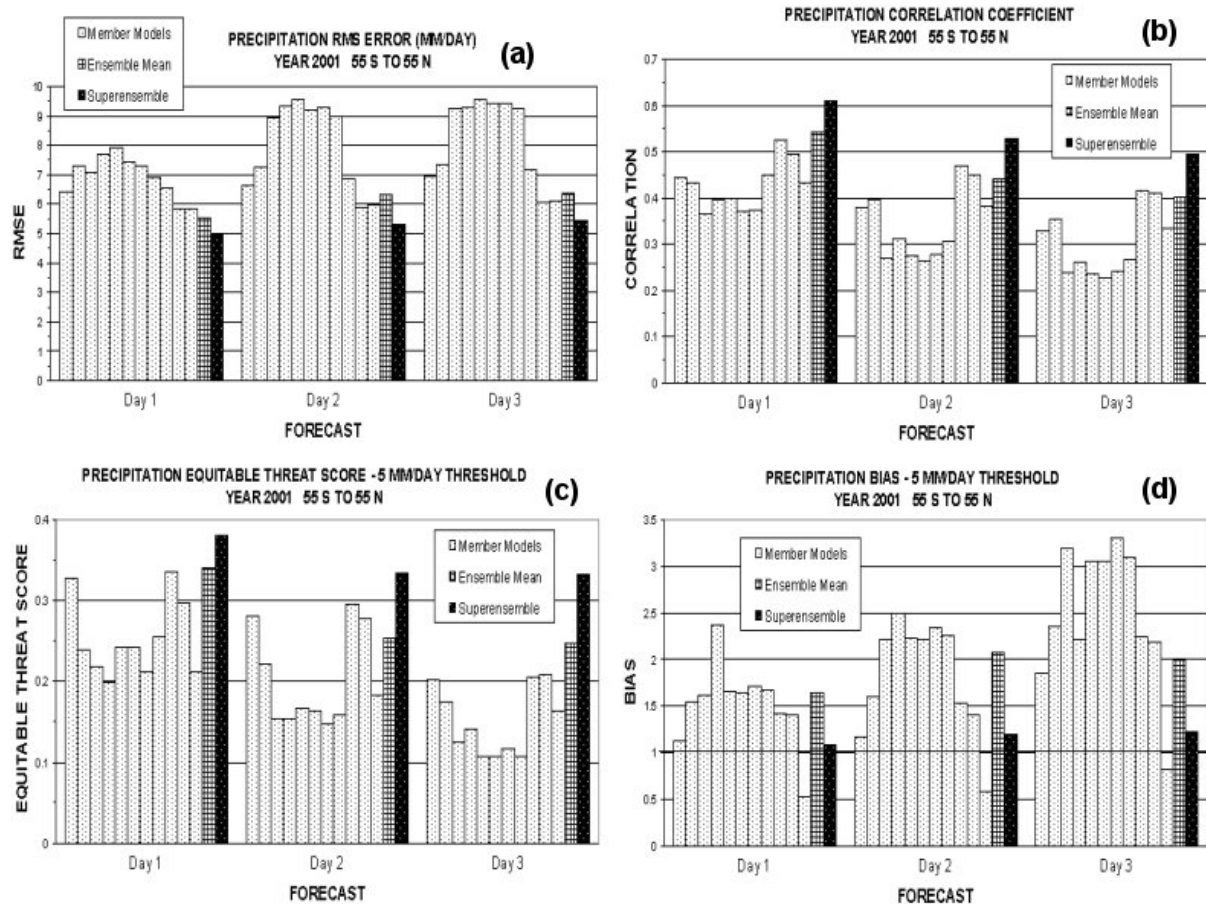
3.   The precipitation superensemble

We have published two recent papers on precipitation forecasts from the FSU superensemble. The first of these, Krishnamurti *et al*., (2000a), was based on a multianalysis superensemble. This included several precipitation assimilation-based initial states. Here we used a number of existing rain rate algorithms, including satellite-based brightness temperatures derived from microwave radiances. This data set comes from four satellites, the NASA TRMM satellite, plus four U.S. Air Force DMSP satellites. These different components of the analysis make use of physical initializations that assimilate these rain rates *via* reverse physical parameterization algorithms. This not only improves the nowcasting skill of rainfall but also modifies the initial divergence, pressure tendencies and moisture profiles consistent with the rainfall rate prescription.

The superensemble method partitions the computations into two time lines. The first is a control (or training) period and the second is a forecast period. During the training phase some 155 experiments were conducted to find the relationship between the forecasts datasets of the training phase and the best observed estimates of daily rainfall totals. The results for day 1, 2, and day 3 forecasts were compared to various conventional forecasts with a global model. For day 3 forecasts of precipitation, the superensemble was noted to have the highest skill in such comparisons.

A more comprehensive study on multianalysis – multimodel precipitation forecasts, Krishnamurti *et al*., (2001), demonstrated further improvements of the methodology. A total of 11 models, of which 5 represent global operational models and 6 represent multianalysis forecasts from FSU models initialized by different rain rate algorithms were included in the multianalysis/ multimodel system. The term "superensemble" is being used here to denote the collective bias corrected forecasts from the "multimodel" and the "multianalysis." The training period was covered here by nearly 120 forecast experiments prior to 1 January 2000 for each of the multimodels. These are all three-day forecasts. The statistical bias of the models is determined from multiple linear regression of these forecasts against a "best" rainfall estimate. The skill of this system was noted to be higher than those of the ensemble mean that assigns a weight of $1/N$ (N being the number of models) to all models including the poorer models. The superensemble skill was also superior to the bias-removed ensemble mean using individual models. The selective weights of the superensemble forecast system make it somewhat superior to individual models and the above mean representations. The skill of the precipitation forecasts was discussed using several different metrics including the standard root mean square (RMS) errors and the correlations of the observed and predicted precipitation totals.

The equitable threat scores at many thresholds of rain were also examined for the various models and for forecast days 1 to 3, a similar higher skill for the superensemble was noted. The results were also noted to hold over five sub-regions of the globe that included North America, Asia, Australia, South America and Africa. Issues on optimizing the number of training days was addressed by examining training with days of high forecast skill *versus* training with low forecast skill. Selective use of the best rainfall forecast days within the training phase appeared to improve the forecast phase.

As a comprehensive extension of previous multimodel/multianalysis superensemble studies of rainfall forecasts, the benefits and prospects of the superensemble precipitation forecasts were explored using satellite products. Three different precipitation ensemble configurations were established from a great number of numerical experiments. These configurations were the multianalysis, multicumulus and multimodel. The multianalysis ensemble set comes from the use of several different satellite-derived rain rates through the physical initialization procedure within the Florida State University Global Spectral Model (FSUGSM) system. Six different state-of-the-art cumulus parameterization schemes were incorporated into the FSUGSM in order to introduce the multicumulus ensemble configuration. Finally, the

Figs. 1(a-d). (a) Annual mean RMS errors of real-time precipitation forecasts (mmday^{-1}) for the year 2001 from multimodels, ensemble mean and superensemble for the domain from 55° S to 55° N (b) Same as Fig. 1 (a) but for correlation coefficient, (c) Annual mean values of bias of real-time precipitation forecasts for values in excess of 5 mmday^{-1} threshold for the year 2001 from multimodels, ensemble mean and superensemble for the domain from 55ºS to 55ºN and (d) Same as Fig. 1 (c) but for equitable threat scores at 5 mm/day threshold

multimodel configuration was composed of an FSU control forecast and those provided by five operational numerical weather prediction centers. In addition to the original technique, a possible deterministic superensemble enhancement technique (*via* a regression dynamic linear model) is then proposed and applied to the above three configurations of ensemble members as well as all of them together. The impact of a higher resolution family of models on the performance of the superensemble forecasts was investigated by repeating the procedure using precipitation forecasts at a resolution of T170. Results show that short-to-medium-range superensemble forecasts were invariably superior in skill to various conventional forecasts. A notably improved quantitative precipitation forecast was provided by the superensemble technique. The multimodel configuration proved to be the most effective prediction system. Although a higher resolution superensemble forecast requires a large amount of

computing time, the impact is significant not only in skill scores, but also in resolving mesoscale-based convective disturbances.

Short-to-medium-range probabilistic precipitation forecasts over the global tropics were explored using satellite products from the Tropical Rainfall Measuring Mission (TRMM), Microwave Imager (TMI) and the Special Sensor Microwave Instrument (SSM/I). In addition to the conventional probability of precipitation forecast, superensemble probability of precipitation forecasts were performed and applied to the multianalysis, multicumulus and multimodel ensemble configurations in two different horizontal resolution forecasts. It was demonstrated that the ensemble system using a single model has a more consistent bias, which can atleast be partially removed by a simple bias correction. With the aid of properly prepared ensemble members, meaningful
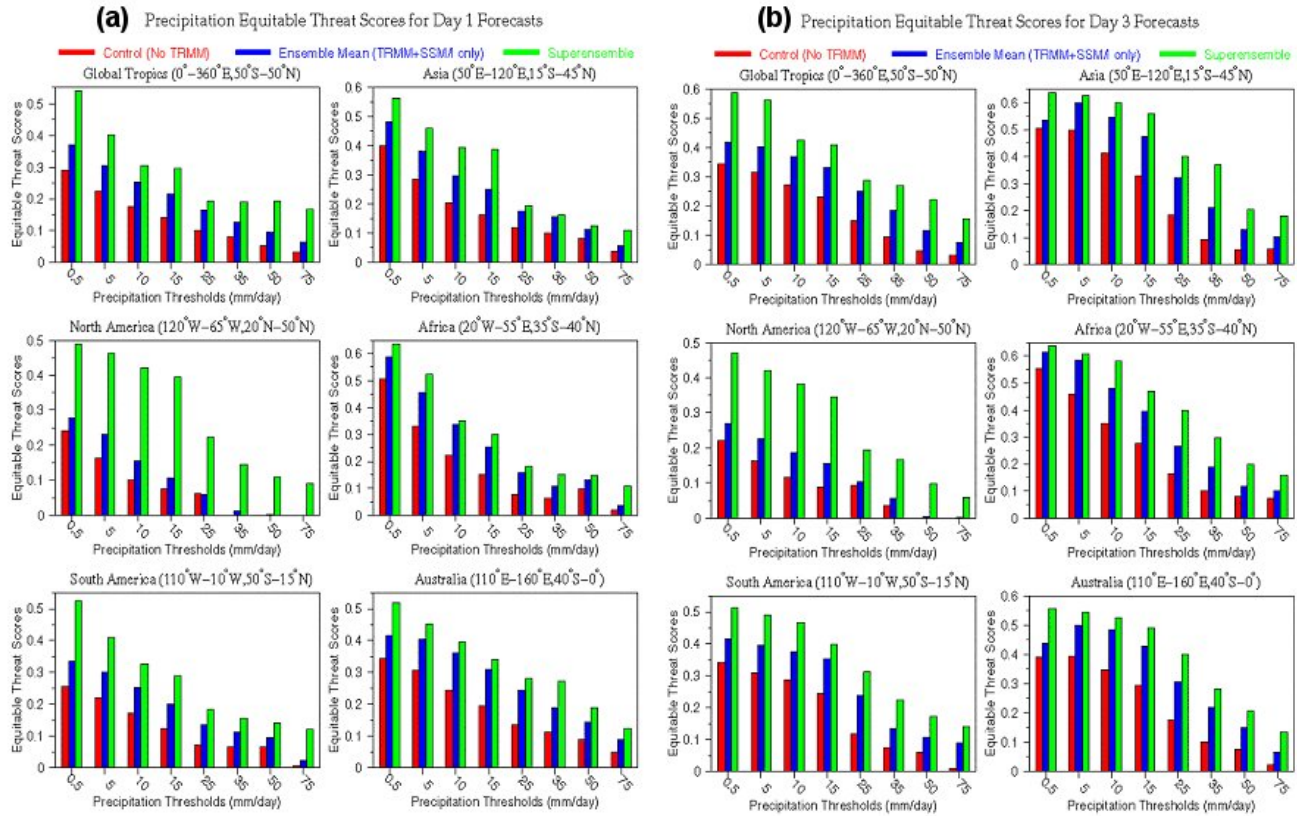
Figs. 2(a&b).   Annual mean equitable threat scores of precipitation for different threshold values from a control experiment (without use of TRMM), ensemble mean and superensemble, for the year 2001, over different regions of the globe and the entire globe, for (a) day-1 forecasts and (b) day-3 forecasts

probability of precipitation forecasts have much longer forecast lead times. Results also showed that a family of higher resolution forecasts has a greater ability to remove model bias.   The advantage of the superensemble approach is found to be evident in making probability of precipitation forecasts compared to the conventional method.

4.   Skills in the prediction of heavy rains

We have been monitoring the performance of these eleven global models using the equitable threat scores on a regular basis. Here we are also examining, on a real-time, the skill scores for the member models, the ensemble mean and the FSU superensemble. Figs. 1 (a-d) illustrates a summary of these scores for the year 2001 for the belt from 55° S to 55° N for days 1, 2, 3 of forecasts. The ordinate in these illustrations denotes the skills such as RMS error [Fig. 1(a)], correlation [Fig. 1(b)], bias [Fig. 1(c)] and the equitable threat scores [Fig. 1(d)].   The abscissa shows the day of forecast. These results clearly show an overall improvement of forecast skills of precipitation from the superensemble.

We next show the equitable threat scores of precipitation for various thresholds of rainfall intervals over different regions of the globe, *e.g*., Asia, North America, Africa, South America, Australia and the entire global belt, Figs. 2 (a&b). Here the skills for forecast days 1 and 3 are illustrated for the year 2001. The green barbs from the superensemble have the highest skill, followed by the skill of the ensemble mean (blue) and the control run (red). Heavy rain in excess of 25 mm and 50 mm per day are shown on the far right side of each histogram. Equitable threat score is a measure of relative success of forecast in terms of predicting a value of rainfall in excess of certain threshold and is expressed usually as:

Equitable Threat Score =

$$\frac{H-\left(F\times\dfrac{O}{N}\right)}{F+O-H-\left(F\times\dfrac{O}{N}\right)} \qquad (0\le \text{ETS} \le 1)$$

TABLE 2

List of flooding events*

Case # and location	Details	Began – Ended (dates shown)	Duration (days)	Casua-lities	Flood type	Area flooded (sq. km)	Notes and comments
Case 1 Sri Lanka	Districts of Ampara, Batticaloa, Anuradhapura,	24-27 Dec, 2000 24-27 Dec, 2000	4	5	Heavy monsoon rains and cyclone rains	13730	The coastal districts of Ampara and Batticaloa were already underwater when the cyclone brought more rain on Tuesday..."
Case 2 Eastern Australia	New South Wales	01-06 Feb, 2001 30 Jan – 1 Feb, 2001	6	1	Heavy rains	110600	Feb 3 -"More than 200 people were evacuated from the state's worst hit town after the Wilson river peaked at 10.41m at 5pm
Case 3 Vietnam	Central Vietnam	15-17 May, 2001 14-16 May, 2001	3	2	Heavy rains	5610	Heavy rains left crops and roads under as much as 240 millimeters (9.5 inches) of water -caused landslides in many places
Case 4 Southern United States	Allison Floods	06-13 Jun, 2001 6 –9 Jun, 2001	8	47	Heavy rain from Tropical Storm	32060	An estimated 20,000 Houston-area residences were flooded by as much as 3 feet of rain that fell after Alison
Case 5 Southern United States	Allison Floods	06-13 Jun, 2001 10 –12 Jun, 2001	8	47	Heavy rain from tropical storm	32060	An estimated 20,000 Houston-area residences were flooded by as much as 3 feet of rain that fell after Alison
Case 6 Brazil	Southeast Brazil	17-25 Dec, 2001 13 – 16 Dec, 2001	9	13	Floods and mudslides - two days of heavy rain	578300	Worst hit was Espirito Santo where seven people were killed by mudslides that swept through hillside shantytowns
Case 7 India/ Bangladesh	NE India, Tripura, Assam and Bangladesh	05-22 Jun, 2001 1 – 4 June, 2001	18	18	Heavy monsoon rains	17560	India's northeast state of Tripura, which was hit by heavy flood, remained cut off from the rest of the country for the third day Friday ... In the neighboring state of Assam, the situation was even worse with more than 200,000 people of nearly 100 villages in the southern part of the state affected
Case 8 Madagascar Mozambique	Cyclones Eline and Gloria	17 Feb-10 Mar, 2000 20 – 23 Feb, 2000	23	200	Rain from two cyclones	256000	Cyclones Eline and Gloria
Case 9 Madagascar Mozambique	Cyclones Eline and Gloria	17 Feb-10 Mar, 2000 2- 5 Mar, 2000	23	200	Rain from two cyclones	256000	Cyclones Eline and Gloria
Case 10 India	Northwest India – Gujarat	20-21 Jun, 2001 14-17 Jun, 2001	2	29	Early monsoon downpour	38730	"Three villages in Baroda 125 kilometers (80 miles) southeast of Ahmedabad, were inundated following the breach in a dam at nearby Pratappura

* (*Source : Dartmouth Flood Observatory*)

The equitable threat score (ETS) evaluates a model's placement of precipitation by comparing the forecasted area of precipitation (*F*) with the observed area of precipitation (*O*), the overlap indicates a "hit" area (*H*). The "equitable" part of the equitable threat score is an adjustment to the threat score to account for the possibility of overlap of areas *F* and *O* due to chance.

The results demonstrated in Figs. 1 and 2 include results from a control experiment that uses a single FSU model that does not include any rain rate initializations, results from an ensemble mean of 11 models, of which 6 models include rain rate initialization, the ensemble mean and results from the FSU superensemble following Krishnamurti *et al.*, (2001). Although the skills for the forecasts of heavy rain (>25 mm/day thresholds) are small, the superensemble-based forecasts can still be useful for providing guidance for flood events. That is a goal of this study.

5. Superensemble forecasts of precipitation for flood and heavy rainfall events

We have made use of the high skill of the precipitation superensemble to examine the possible use of this product for guidance in recent floods. A number of episodes of heavy rains were examined (Table 2). In each case we prepared the following set of illustrations:

(*i*) Observed 24-hourly rainfall totals for a sequence of days during a flood/heavy rainfall event.

(*ii*) A sequence of day-1 to day-4 rainfall forecasts during the flood episode from the superensemble.

(*iii*) A sequence of day-1 to day-4 rainfall forecasts during the flood episode from the best member model.

(*iv*) Maps of 4-day rainfall totals during the flood event from (a) an observed estimate, (b) the FSU superensemble and (c) the best member model and

(*v*) Area averaged storm rainfall totals (shown as a histogram) for the observed estimates, the FSU superensemble and the best member model.

A sequence of these illustrations for selected flood events is presented in this section. This product does appear to provide useful guidance up to 3-4 days for heavy rains during a flooding event.

5.1. *The Assam/Bangladesh floods*

Monsoon rains of the year 2001 caused extensive flooding and landslides in south Asian countries. Disastrous flood events reportedly submerged the homes of more than two million people and left atleast 80 dead in northeast India, in particular in the states of Assam and Bihar. Monsoon rains also triggered devastating landslides in the central highland region in Bhutan and flash floods were also reported in Bangladesh. Since the onset of the southwest monsoon in June, several states in India have received heavy rainfall resulting in floods, loss of human life and cattle, loss/damage to houses and property and dislocation of normal activities. About 89% of the country received normal to excessive rainfall. Instances of serious floods occurred during the month of June in Assam, Tripura, Chhattisgarh, Central India, Orissa, Nepal and Bangladesh.   Heavy rains in the catchment areas of the Barak river (Mizoram, west Manipur and south Catchar, Karimganj and Hailakhandi districts of Assam), torrential rains in the west and north districts of Tripura and sudden floods over Karimganj, Silchar, Tripura and Jawai (Meghalaya) districts during 1-4 June 2001 caused major havoc in northeast India and neighboring places, including parts of Nepal and Bangladesh. Out of the four districts, the west Tripura district received the worst impact of the floods in 25 years. Roughly 20 million people in the affected areas were evacuated and more than 60 people died from these floods. The national highways connecting regions of Mizoram, Tripura and south Assam were seriously damaged. Over 600,000 people were displaced from their homes due to heavy rains and flooding in the northeastern state of Tripura and Assam alone. In Nepal, 35 people were reportedly killed in floods and landslides triggered by heavy monsoon rainfall in the Satya Devi village of Dhading district.

Figs. 3 and 4 describe the forecast of this flooding event by the superensemble and the best model, respectively, in the northeast parts of India and Bangladesh from 1-4 June 2001. The top four panels in Figs. 3 and 4, from left to right, show the series of observed 24-hr accumulated rainfall derived from the TRMM and SSM/I data sets during the same time period. The subsequent rows in each of these diagrams illustrate the forecasts from the real-time FSU superensemble and a best member model, valid on the same dates as those of the observed panels. The flooding pattern is well captured by the superensemble forecasts and is closer to the observed through day 4 of the forecast.   The intense precipitation over the northern Bay of Bengal coast and along the Bangladesh coast is well represented by the superensemble. The best model forecasts displayed in Fig. 4 do not carry any skill; even for day-1 forecasts the model failed to represent the heavy rainfall events. This skill is further degraded by day-3 and day-4 forecasts where the model started producing fictitious heavy rainfall over the northern and eastern parts of India on 4-5 June. The total 4-day accumulated rainfall amounts from the observed (TRMM + SSM/I), superensemble and the best
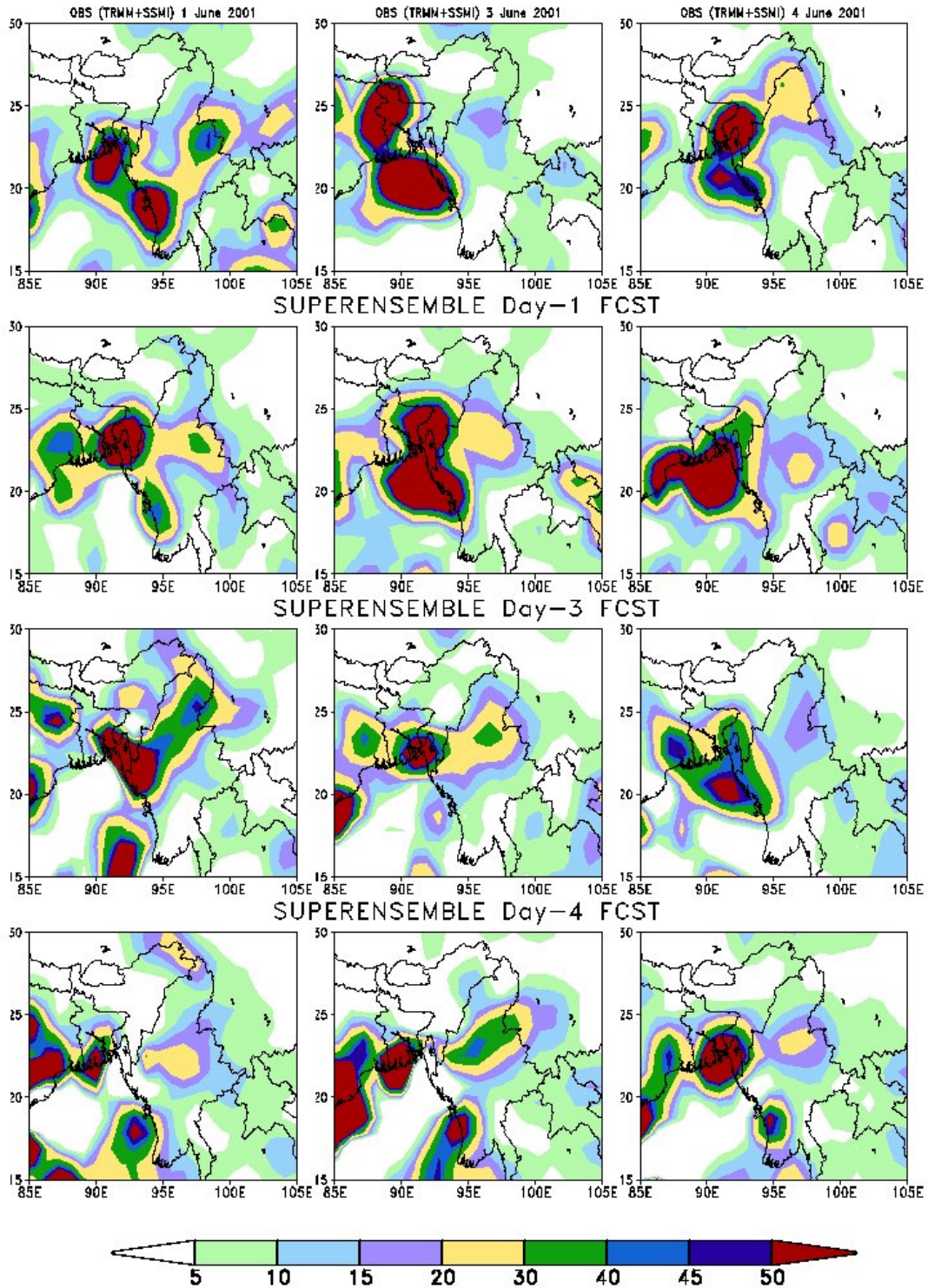
Fig. 3. A sequence of observed rainfall (mmday^{-1}) and 4-day forecasts from the superensemble valid on the observed dates for Northeast India and Bangladesh region during June 1, 2 and 4, 2001 (shown are the day-1, day-3 and day-4 forecasts)

model are displayed in Figs. 5 (a-c). This figure clearly illustrates the capability of superensemble forecasts in providing guidance for heavy rainfall events. The amounts of rainfall in excess of 200 mm over a 4 day period in the northeast parts of India and west coast of Bangladesh were well represented by the superensemble
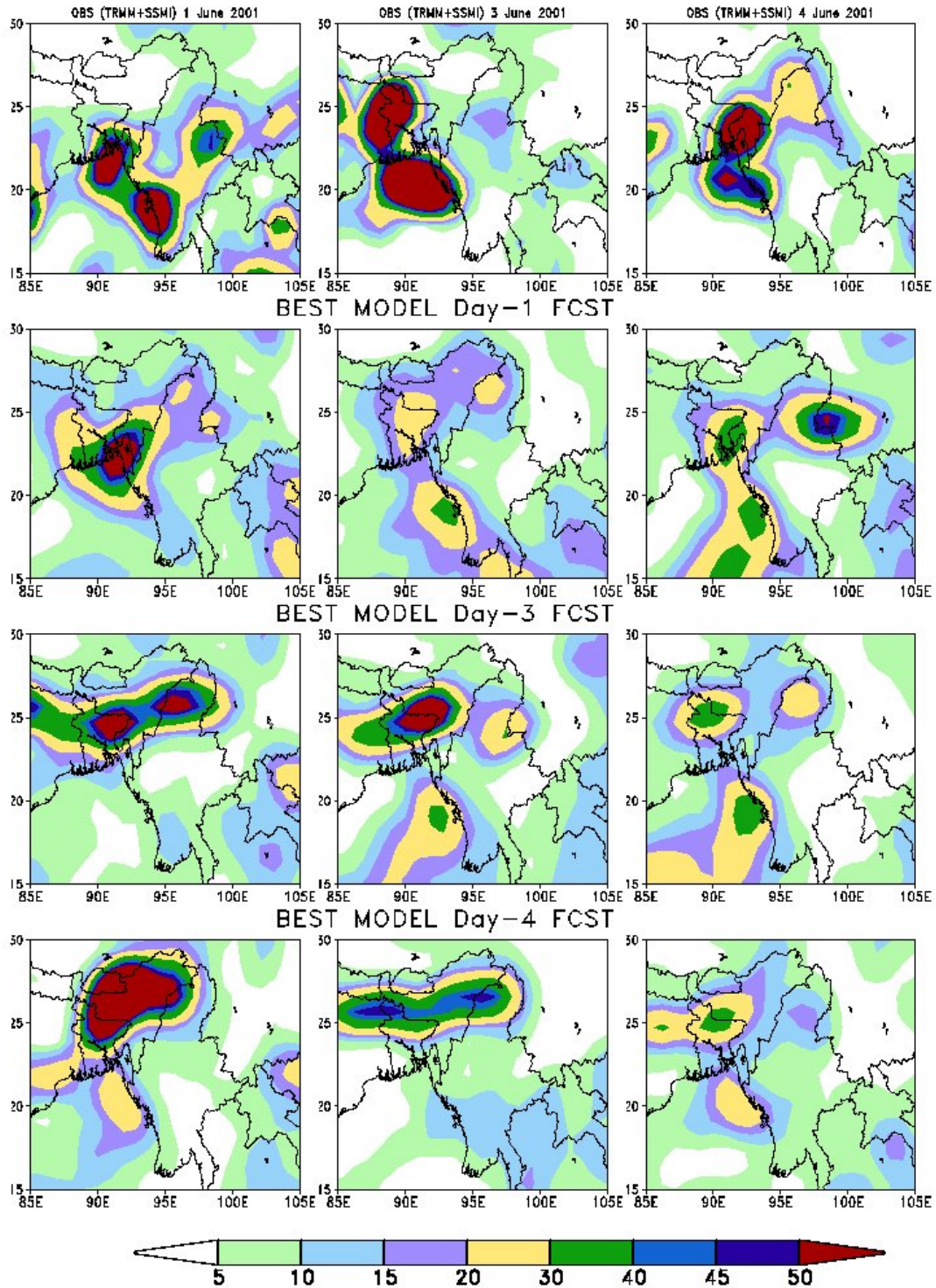
Fig. 4.   Same as Fig. 3 but for forecasts from the best model

forecasts while the best model forecast under-predicted the total rainfall amount and also displaced the heavy rainfall zone to the north of the region where floods occurred (similar diagrams for some other flooding events discussed later in the manuscript are shown in Figs. 6, 7 and 8). The area averaged daily forecasts of total rain

Fig. 5   Fig. 6   Fig. 7   Fig. 8
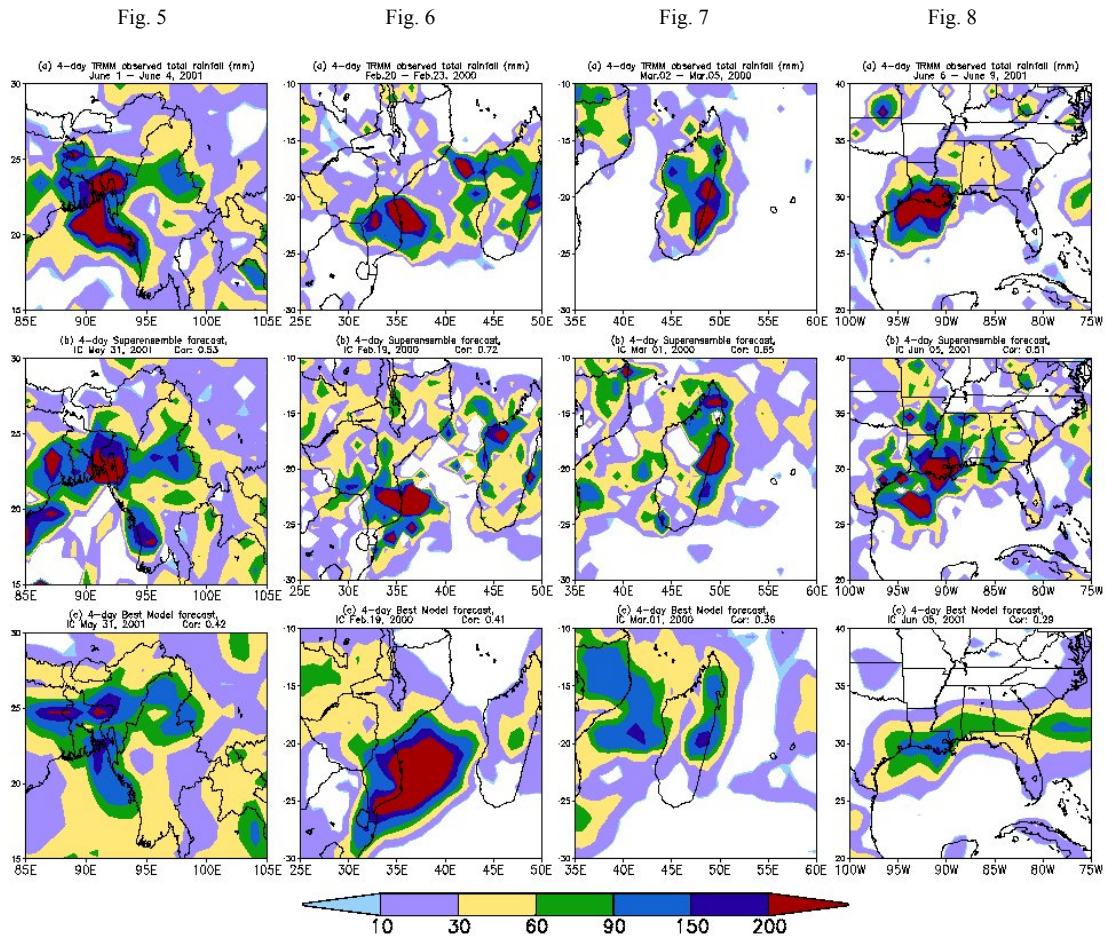
Figs. 5(a-c). 4-day accumulated rainfall (mm) (a) top panel shows the observed estimates from TRMM/SSM/I, (b) middle panel shows forecast from the superensemble and (c) bottom panel shows forecast from the best model. 1-4 June, 2001, over the Northeast India and Bangladesh region

Figs. 6(a-c). Same as Fig. 5, except for 20-23 February, 2000 over the Mozambique/Madagascar region

Figs. 7(a-c). Same as Fig. 5, except for 2-5 March, 2000 over the Mozambique/Madagascar region

Figs. 8(a-c). Same as Fig. 5, except for 6-9 June, 2001 over the Gulf coast region of the United States

over the region of flooding are shown in Fig. 9. Here the histograms show 4-day forecasts of rainfall totals obtained from superensemble, the best model and the observed estimates. The superensemble demonstrates a marked improvement in predicting heavy rains throughout the forecast period compared to the best model, which tends to under-predict the intensity of rain rates and fails at longer integrations beyond day 1.

5.2. *The Mozambique/Madagascar floods*

Catastrophic flooding occurred in Mozambique during the periods 20-23 February and 2-5 March of 2000. A very active ITCZ was positioned along 5° S and southeasterly trade winds swept from the Indian Ocean across Madagascar into Mozambique and Zimbabwe bringing moisture and supporting the development of disturbances on the northern or cyclonic shear side of this flow. The situation was greatly compounded by two tropical cyclones that affected the flooded regions. The first of these was Tropical Storm Eline which moved from the Indian Ocean across Madagascar and into the Mozambique channel around 18 February. On 22 February this storm made landfall over the central Mozambique coastal region near the town of Beira with winds of 71.5 m/s (139 knots or 160 mph). Great destruction resulted on the southern side of Eline and torrential rains produced the worst flooding of the period under study. The second tropical cyclone was Gloria, which formed over the Indian Ocean in early March and
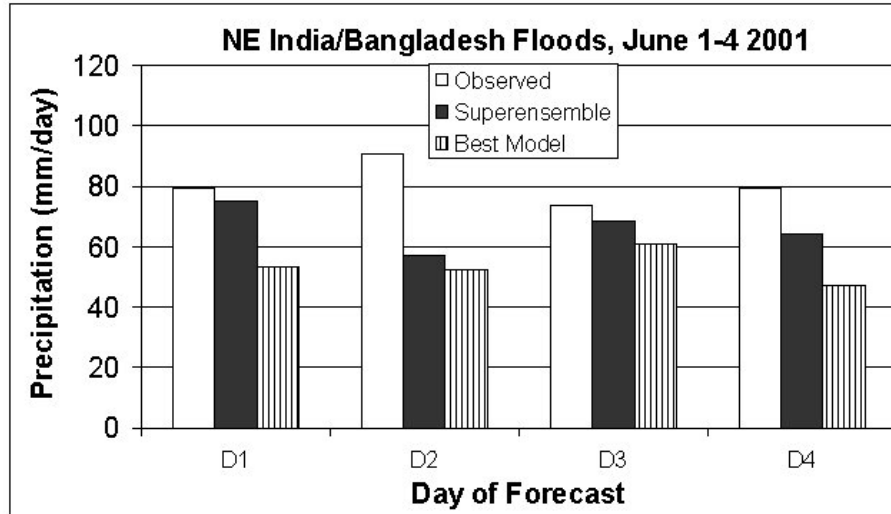
Fig. 9. Storm total rainfall values (mm) over the flood region for observed estimates, superensemble and best model for different days of forecast. Shown are the results over Northeast India and Bangladesh region for the period during 1-4 June, 2001

moved westward across Madagascar. Although the storm weakened before reaching Mozambique its remnants still managed to produce very heavy rain that contributed significantly to the second flooding episode of 2-5 March. In both of the flooding events the heaviest rains fell in the headwaters of the Limpopo River over Zimbabwe resulting in a cresting of the river over southern Mozambique where the flooding was the most extreme. The floodwaters took hundreds of lives and left thousands homeless as they destroyed roads, railways, houses, cattle and crops.

The first flooding episode of 20-23 February is depicted in Figs. 10&11. In Fig. 10 the observed precipitation for each day is depicted based on TRMM and SSM/I observations along with the predicted precipitation from the superensemble. In the superensemble product we see day-1 through day-4 predictions (except day-2) verifying on the date of the observed precipitation. In the observed graphics a region of enhanced rainfall is seen extending generally from Madagascar across the Mozambique channel into Mozambique and Zimbabwe. More specifically, a region of heavy rain in excess of 200 mm/day is seen to move from the Mozambique channel into Mozambique during 21-22 February and then into Zimbabwe by 23 February. This is the torrential rain associated with Tropical Storm Eline. The superensemble can be seen to give a very good prediction of this tropical storm rainfall in forecasts as far out as 3 days. It is only in the day-4 forecasts that the event is not well predicted. In Fig. 11 the performance of the best model is shown for comparison. These predictions

are not as good as those of the superensemble in terms of both timing and areal coverage of the precipitation. Day-1 forecasts are the best, but even here the areal coverage of the precipitation is overdone and the precipitation region is too far inland and too far to the north over Zimbabwe. In longer-term forecasts the areal extent of the precipitation is overdone and for day-3 and day-4 forecasts the precipitation area is along the coast and not inland as observed.

In Fig. 6 the 4-day total rainfall for the 20-23 February event is shown as predicted by the superensemble and best model, as initialized on 19 February. Also shown is the observed 4-day total rainfall from TRMM. The superiority of the superensemble forecast is immediately apparent. The correlation score for the observed *versus* predicted rain is 0.72 for the superensemble and only 0.41 for the best model. The superensemble accurately predicts the location of rainfall maxima over Mozambique and Madagascar and captures the appropriate size of the regions with rainfall in excess of 200 mm. The best model, on the other hand, under-represents the rainfall over Madagascar while it over-predicts the region with rainfall in excess of 200 mm farther to the west, improperly holding it over the Mozambique channel and not allowing it to migrate inland as observed.

The second flooding event during 2-5 March is treated in Fig. 7. Here the domain is centered on Madagascar to capture rain associated with Tropical Storm Gloria, which struck that island and then weakened
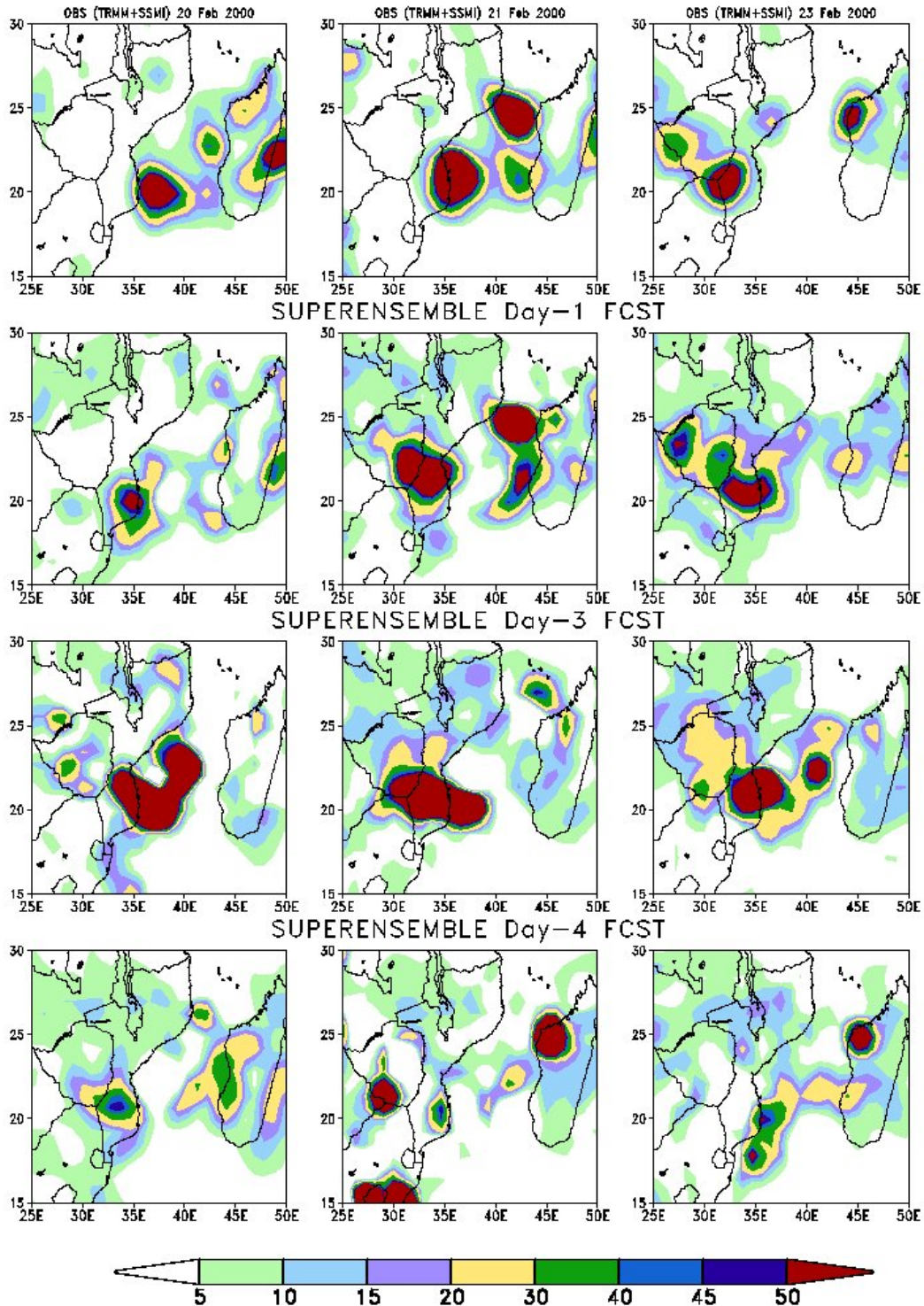
Fig. 10.   A sequence of observed rainfall (mmday^{-1}) and 4-day forecasts from the superensemble valid on the observed dates for Mozambique/Madagascar region during 20-23 February, 2000. (shown are the day-1, day-3 and day-4 forecasts)

as it migrated westward into Mozambique. In this figure the observed 4-day total rainfall is shown from TRMM observations. The predicted rainfall by the superensemble and best model is an accumulated 4-day rain from a forecast initialized on 1 March. The superensemble's prediction is superior to that of the best model, with
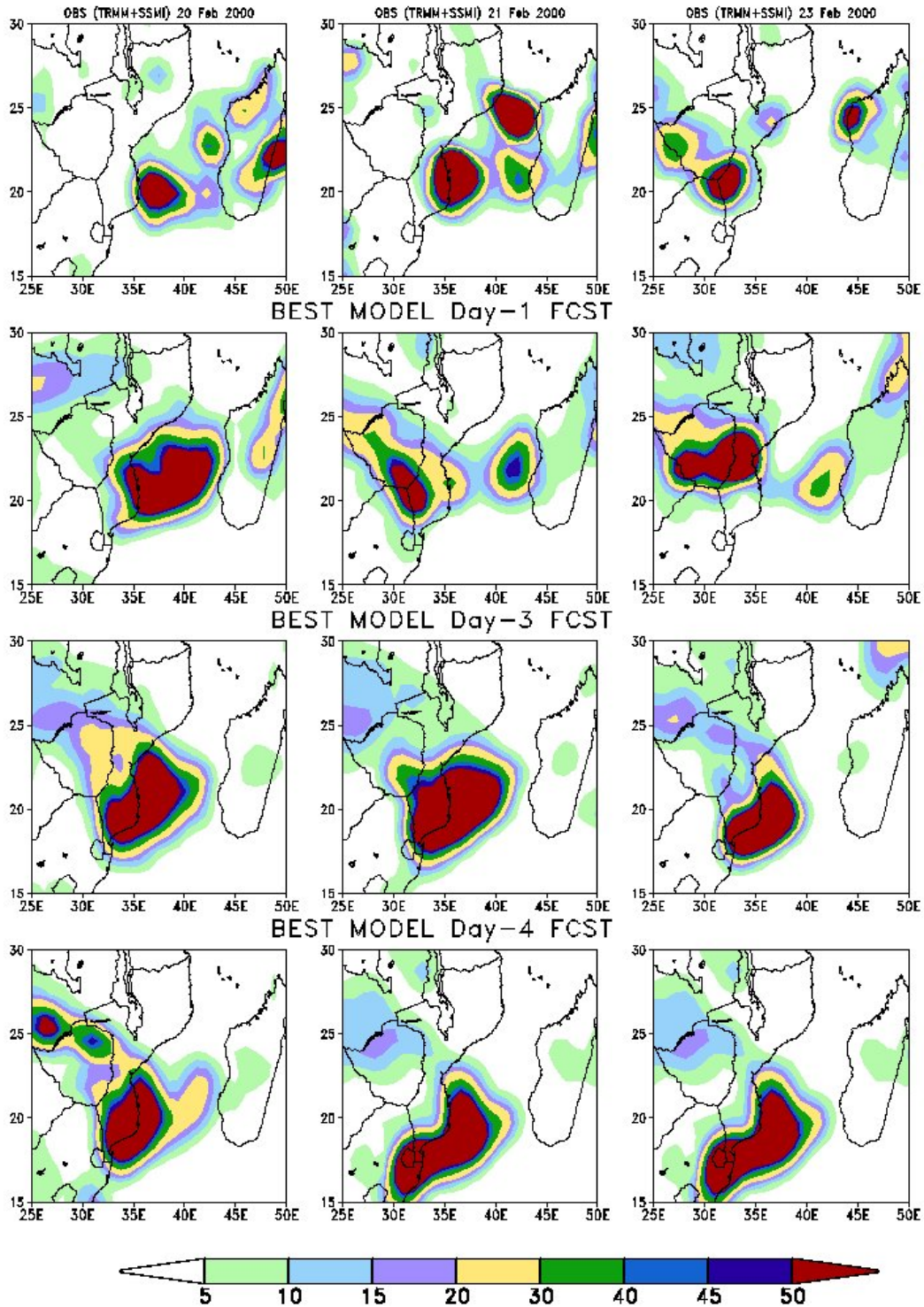
Fig. 11. Same as Fig. 10 but for forecasts from the best model

correlation scores of 0.65 and 0.36 respectively. The superensemble captures the rainfall maximum in excess of 200 mm along the east coast of Madagascar while the best model does not. The best model erroneously shows large rainfall amounts extending across the Mozambique channel with values in excess of 150 mm. The observed
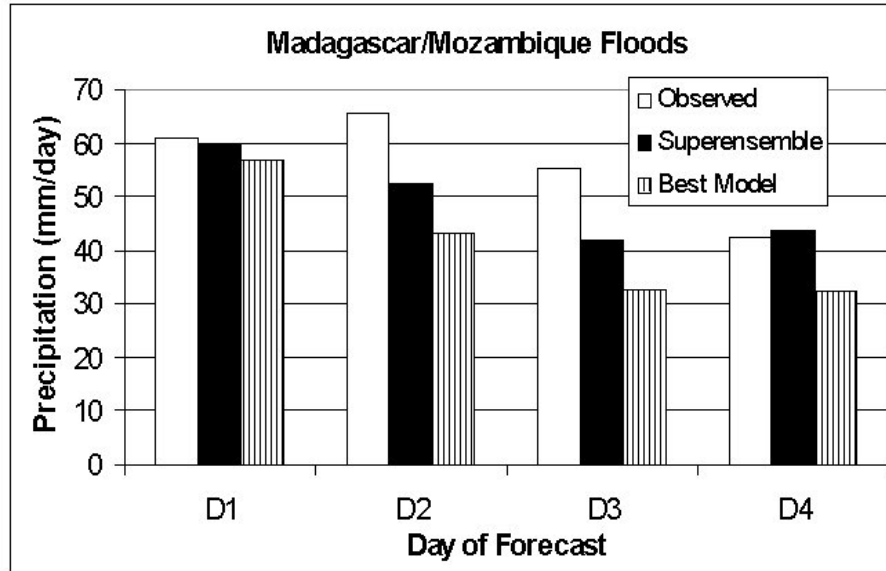
Fig. 12. Storm total rainfall values (mm) over the flood region for observed estimates, superensemble and best model for different days of forecast. Shown are the results over Madagascar/Mozambique region for the period during 2-5 March, 2000

rainfall map shows very little rain in this region. The superensemble shows some rainfall in the channel but not as much as the best model. Finally, the superensemble better handles rainfall totals over Mozambique than the best model; the best model over-predicts the amounts, whereas the superensemble values are close to the observed amounts.

In Fig. 12 the domain averaged observed daily rainfall totals for the period 2-5 March are shown based on TRMM observations, along with the domain averaged predicted daily rainfall totals for the same period from the superensemble and best model. The predicted rainfall is from a forecast initialized on 1 March. It can be seen that the superensemble forecasts are much closer to the observed rainfall for each of the forecast days. The superensemble avoids the under-forecasting of rain seen in the best model, matching the observed rainfall almost perfectly in the day-1 and day-4 forecasts.

5.3. *Tropical Storm Allison floods over the Gulf coast of the USA*

Tropical Storm Allison was the all-time costliest tropical storm to affect the U.S. Although Allison's maximum sustained winds were never stronger than about 25 ms^{-1}, it meandered over eastern Texas for four days from 5-9 June 2001, first moving northward then southward back over its original landfall location and into the Gulf of Mexico. During this time, Allison produced substantial flooding across portions of southeast Texas,

especially in the vicinity of Houston, where a storm total maximum of 939.5 mm (36.99 inches) of rain fell at the Port of Houston. Allison then moved across Louisiana dumping a storm total maximum of 758.4 mm (29.86 inches) in Thibodaux (Evans *et al.*, 2001). Allison continued an eastward motion across the Gulf Coast before entering North Carolina and eventually exiting the mid-Atlantic coast on 18 June. Forty-one people lost their lives, of which twenty-seven were due to freshwater flooding. The Federal Emergency Management Agency (FEMA) estimates damages of nearly $5 billion from this historic storm, mostly in the Houston area (Stewart 2001).

Two separate superensemble forecasts for Allison floods were examined. The first was from 6-9 June 2001 focusing on Texas and Louisiana (Figs. 13&14 and Fig. 8) and the second was from 10-12 June 2001 over the central and eastern Gulf Coast (Fig. 15). The superensemble performed quite well on these floods. For 6-9 June 2001, the day-1 superensemble predicted heavy rains above 200 mm in many of the same areas where the observations exceeded 200 mm. This is shown in Fig. 13. In addition, for 9 June 2001, there is very good agreement between the observations and superensemble, even out to day-4. On the other hand, for that same day, Fig. 14 shows that the best model performed poorly with respect to the placement of heavy rainfall. Whereas the heaviest observed rainfall was over the northwestern Gulf of Mexico and adjacent coastal areas, the best model's predicted rainfall was much farther east over the
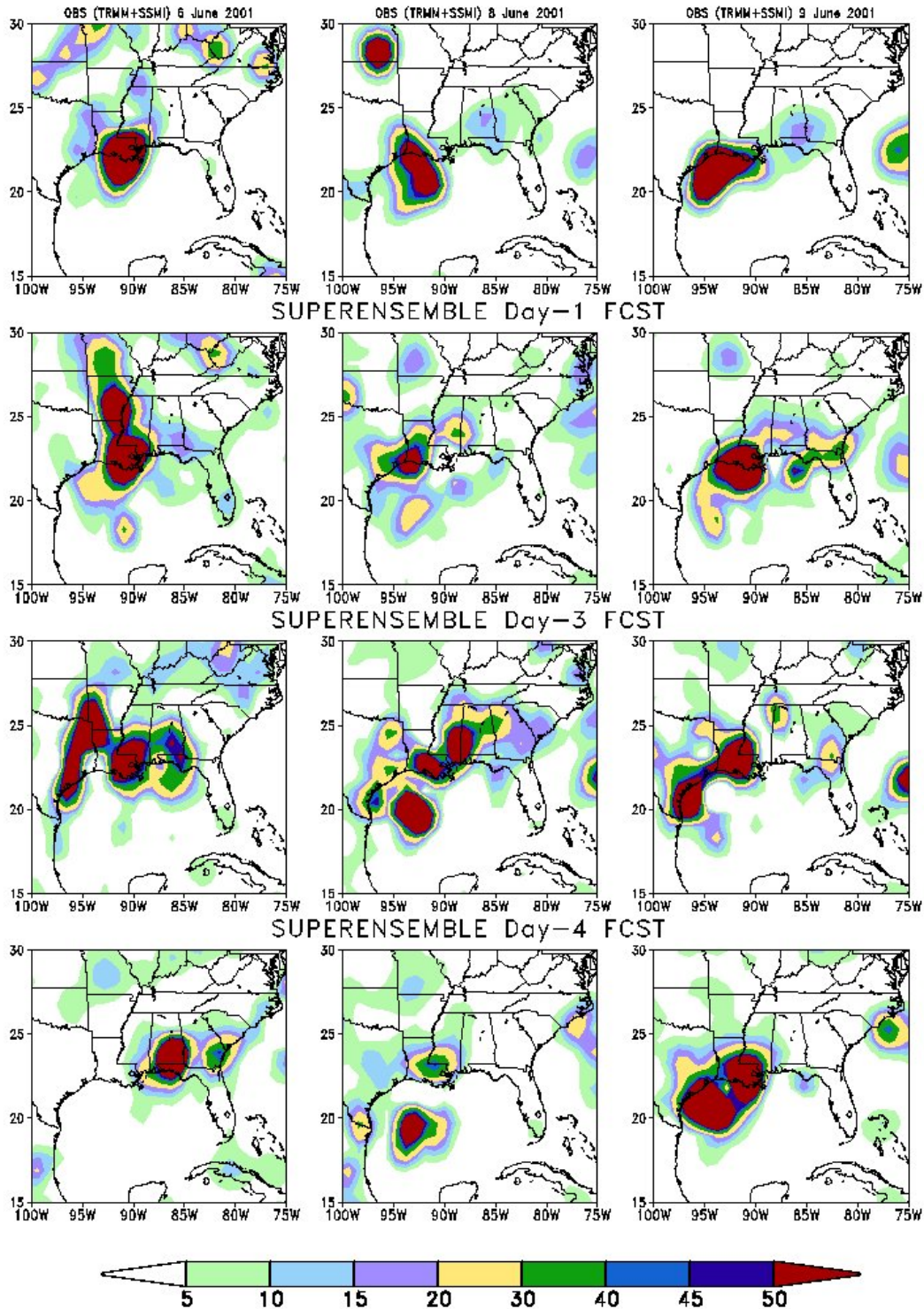
Fig. 13.   A sequence of observed rainfall (mmday^{-1}) and 4-day forecasts from the superensemble valid on the observed
dates for Gulf coast region of the United States during 6-9 June, 2001

southeastern U.S. Furthermore, the best model's rainfall intensity dropped off considerably with increasing lead-time to day-4 of the forecast. Thus, the correlation for the 4-day forecast (Fig. 8) of accumulated precipitation (initial conditions on 5 June) was only 0.29 for the best model, while it was 0.51 for the superensemble forecast.
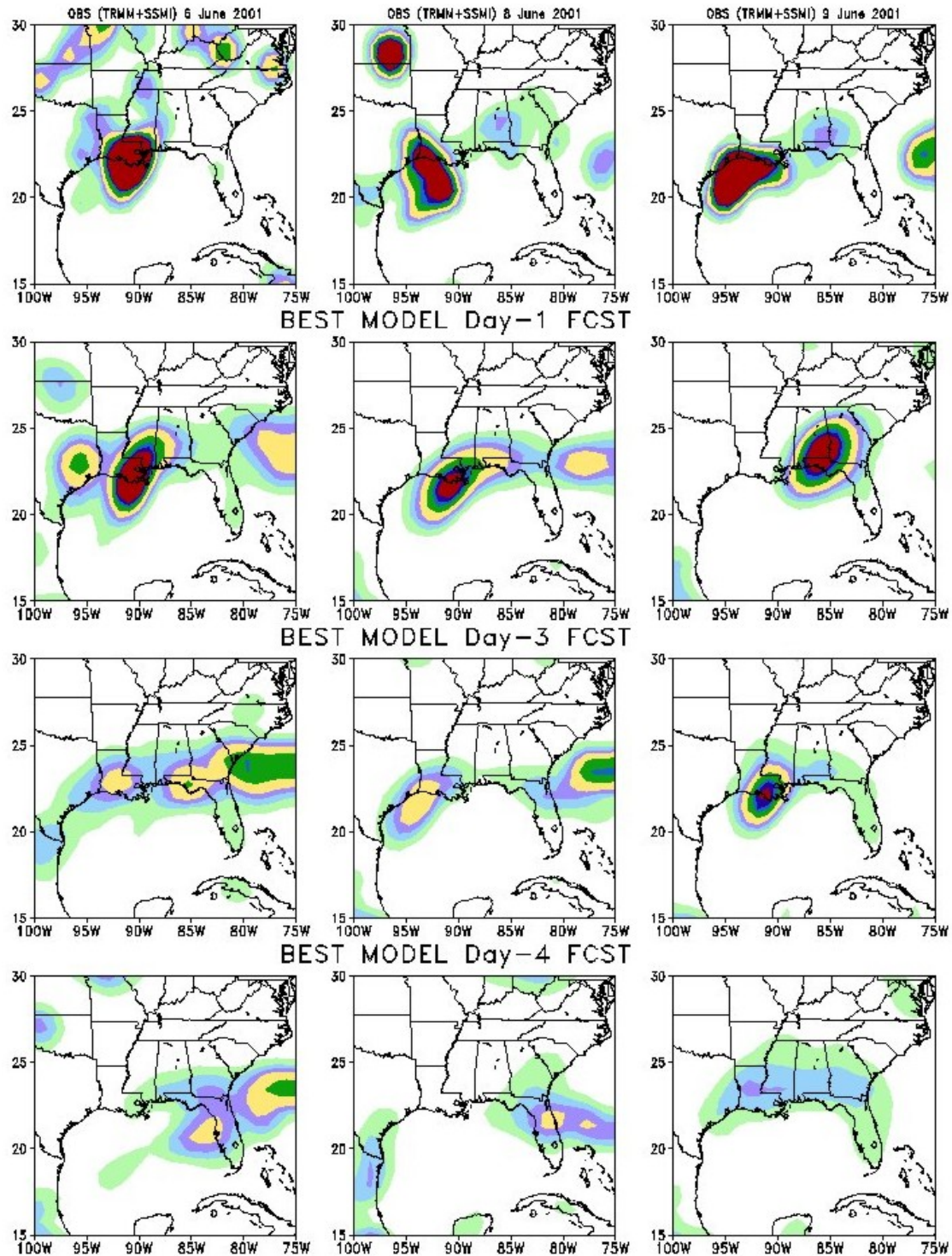
Fig. 14. Same as Fig. 13 but for forecasts from the best model

The second case (*i.e.*, the later period of Tropical Storm Allison) was similar to the first in that the 3-day superensemble accumulated rainfall correlation was 0.67

while the best model's forecast correlation was only 0.37 (not shown). In Fig. 15 the domain averaged observed daily rainfall totals for the period 10-12 June 2001 are
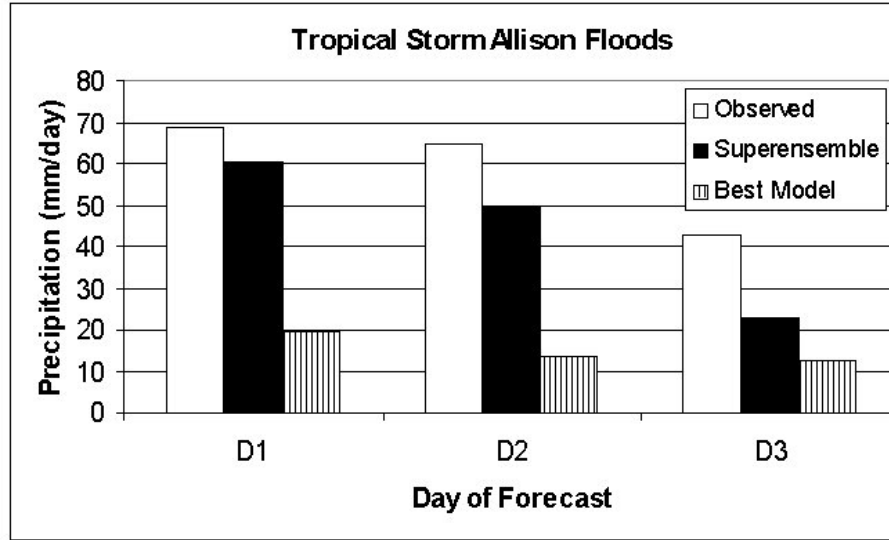
Fig. 15. Storm total rainfall values (mm) over the flood region for observed estimates, superensemble and best model for different days of forecast. Shown are the results over Gulf coast region of the United States during 10-12 June, 2001

shown along with the domain averaged predicted daily rainfall totals for the same period from the superensemble and best model. Superensemble forecasts are closer to the observed rainfall while best model was unable to reproduce the intensity of rainfall for each of the forecast days. While there are some timing issues with these superensemble forecasts, it far outperformed the best model when viewing the day-by-day forecast details (not shown here). The heaviest rains in the best model were found over Georgia and the Carolinas, whereas the superensemble more correctly placed the intense rains along the entire Gulf Coast.

5.4. *Walking through a heavy rain computation during a recent flood episode over western Philippines*

In Table 3, we present a sequence of computations that highlight the heavy rain forecast over western Philippines during the passage of Typhoon Halong during July 2002. In this table the first column identifies 9 of the member models. The training coefficients for the superensemble are shown in column 2, these are based on the predicted rain by the member model during the proceeding 120 days (roughly). The predicted rain for day 3 of forecasts (a 24-hour total); the ensemble mean of forecasts, observed rain, the superensemble based rainfall forecast and the bias removed ensemble mean rainfall forecast are also provided in column 2. The third column shows the mean precipitation $\bar{F}_i$ of the member models during the training phase. The fourth column shows the

value of superensemble function $a_i(F_i - \bar{F}_i)$ for each of the member models. The sixth column shows the bias corrected forecast for each model. The last column shows the forecast error for each member model, it also include the errors for the ensemble mean, for the superensemble and for the bias corrected ensemble mean. An examination of this table show that the coefficient ranges from 0.01 to 0.60. All models underestimate the rainfall on day 3. These coefficients do not reflect this single case, they show the behaviour of the member model during the past 120 days.

The mean rain of the training phase $\bar{O}$ was 26.14 mm/day at the location. That added to $\sum_i a_i(F_i - \bar{F}_i)$, shown in column 5 provides the superensemble forecast. The superensemble forecast of rain for day 3 was 101.71 mm/day. The observed rain 110.44 mm/day. The best model forecast at this location for day 3 of forecast came from the NCEP model. This was not true at all locations and at all ranges of forecasts. The ensemble mean forecast of rain was 51.65 mm/day; the bias correlated ensemble mean was slightly better, *i.e.*, 61-89 mm/day. If we were to proceed to an adjacent region, away from this typhoon, on the same day of forecast, we can still see a superior performance of the superensemble although the best model may not be NCEP. This is shown in Table 4 for comparison purposes. Here the BMRC model exhibited the best forecast among the member models. At this location, the relative spread of statistical weights is

TABLE 3

Walking through a day-3 superensemble precipitation forecast $S = \overline{O} + \sum_{i=1}^{N} a_i \left(F_i - \overline{F}_i \right)$

Multimodel superensemble precipitation forecast from 48 h to 72 h valid
from 20020709/1200 UTC thru 20020710/1200 UTC Valid at 15.43 °N, 120.00 °E
(western shore of Luzon, Philippines)
Precipitation (mm)

Model	Coefficient a_i	Precipitation forecast F_i	Mean precipitation forecast $\overline{F}_i$	$a_i \left(F_i - \overline{F}_i \right)$	$\overline{O} = 26.14$ $\overline{O} + \left(F_i - \overline{F}_i \right)$	Error (mm) $F_i - \text{OBS}$
BMRC	0.60191	88.38	31.52	34.23	83.00	-22.06
FSUFER	0.01805	19.38	11.40	0.14	34.12	-91.06
JMA	0.08609	60.46	12.73	4.11	73.87	-49.98
NCEP	0.22313	91.68	15.89	16.91	101.92	-18.76
NRL	0.22343	57.33	10.64	10.43	72.82	-53.11
RPN	0.08697	78.36	20.21	5.06	84.29	-32.08
FSUCTL	0.43546	24.98	18.00	3.04	33.12	-85.46
FSUOLS	0.08800	23.94	11.46	1.10	38.61	-86.50
FSUTRM	0.06130	20.32	11.23	0.56	35.22	-90.12
ENSMEAN		51.65				-58.79
OBS		**110.44**				
SUPENS		101.71				-8.73
BIAS-REM ENSMEAN		61.89				-48.55

somewhat different. This is located at the South China Sea where the observed rainfall was 85.89 mm/day. The overall performance of the superensemble is similar over most regions of the tropics. While the models undergo considerable relative spreads in their forecast from one region to another, the superensemble appears to be more consistent in its overall performance. It is also of interest to note that the forecast errors of the ensemble mean and of the bias removed ensemble mean. It is important to note that no simple relation exists between higher value of the weights (from training) and the forecast of rain in a specific case. For instance, over the South China Sea, the FSU control experiment (FSUCTL) has the highest weight, however, the forecast of rain is poor at this location for this rain event.

6.   Concluding remarks

This is an ongoing work on real-time short-range prediction of heavy rain. The eleven global models used in this study have a horizontal resolution of roughly 80 km. The multimodel superensemble based on these eleven models does seem to carry some useful information and guidance for heavy rain forecasts in the time frame of 1 to 5 days. We are currently extending this work to a multimodel superensemble for mesoscale models where the resolution is being doubled. The present study benefited from the use of rain rate initialization (called physical initialization) where satellite-based estimates of rain rates were directly assimilated in five of the eleven model runs. Here we noted that the use of data sets from TRMM and DMSP satellites were particularly very useful. We had looked at as many as 10 recent flood events. These carry the typical results from the FSU superensemble. The four examples described in this study are of the floods over northeast India and Bangladesh, the Gulf coast of the USA, Mozambique/Madagascar and the Philippines. The 5- day forecasts of heavy rains in excess of 25 mm/day carry an equitable threat score of around 0.2 to 0.3 from the FSU superensemble. This is twice to thrice more than that of the best model. All of these forecasts of heavy rain appear to have similar skill scores.

TABLE 4

Walking through a day-3 superensemble precipitation Forecast $S = \overline{O} + \sum_{i=1}^{N} a_i \left(F_i - \overline{F}_i \right)$

Multimodel superensemble precipitation forecast from 48 h to 72 h valid from 20020709/1200 UTC
thru 20020710/1200 UTC Valid at 16.36 deg N, 116.25 deg E (South China Sea)
Precipitation (mm)

Model	Coefficient a_i	Precipitation forecast F_i	Mean precipitation forecast $\overline{F}_i$	$a_i\left(F_i - \overline{F}_i\right)$	$\overline{O} = 17.70$ $\overline{O} + \left(F_i - \overline{F}_i\right)$	Error (mm) F_i - OBS
BMRC	0.49539	96.73	10.75	42.59	103.68	+10.84
FSUFER	0.16146	17.09	12.71	0.71	22.07	-68.80
JMA	0.21269	34.56	10.59	5.10	41.67	-51.33
NCEP	0.27851	57.93	6.02	14.46	69.61	-27.96
NRL	0.22542	7.01	3.62	0.76	21.09	-78.88
RPN	0.12789	40.31	13.70	3.40	44.30	-45.59
FSUCTL	0.60904	23.30	15.31	4.87	25.69	-62.59
FSUOLS	0.22708	18.64	10.25	1.90	26.08	-67.26
FSUTRM	0.21834	25.91	11.78	3.09	31.83	-59.98
ENSMEAN		35.72				-50.17
OBS		**85.89**				
SUPENS		94.58				+8.68
BIAS-REM ENSMEAN		42.89				-43.00

The Gulf coast of the U.S. experienced heavy rain from the passage of hurricane Allison. The Mozambique rains were largely attributed to the arrival of a tropical storm from the Mozambique channel and the southern Indian Ocean. The heavy rains over Assam and Bangladesh were largely orographic during an active spell of the monsoon. A horizontal resolution of approximately 80 km was able to resolve these heavy rains. However, it is clear that further work is necessary to examine these episodes with regional higher resolution models. Although an equitable threat score of 0.3 may appear small, we have noted that most operational models, even on day-1 of forecasts, carry such scores. Our skills from the FSU superensemble on days 1 and 2 are generally as large as 0.5 and 0.4 respectively. This appears quite promising for the guidance on possible flooding events.

A priori we do not know which model may be the best one for forecasting heavy rain and providing guidance for a possible flood event. However, we do know that the superensemble would be somewhat better than the best model in predicting heavy rain during a possible flood event.

With the advent of improved techniques for better prediction of heavy rains, a further step is to predict the effects of flooding rains on individual watersheds by using a physically based spatially distributed hydrologic model, such as that developed at the Pennsylvania State University and Harvard University (Yildiz, 2001). This model utilizes a one-dimensional surface flow routing model, a one-dimensional land surface model, and a two-dimensional lateral subsurface flow routing model. The hydrologic model is driven by atmospheric forcing data (*i.e.*, shortwave and longwave radiation at the surface, near surface humidity, temperature, pressure and wind velocity and precipitation) from a global model in this case.

Initial hydrologic simulations have been performed for the Mozambique floods of February 2000 at a spatial scale of 10 km over the Limpopo River basin. These preliminary model simulations did produce promising results. Further experiments are set to begin for longer time periods and for higher spatial resolutions up to 1 km. Moreover, different superensemble methods that use precipitation data are being investigated. Further

improvements will almost certainly be possible with the addition of surface rainfall observations from the Limpopo watershed into the training data set. Mesoscale models may also be considered as inputs to a multi-model superensemble. Yet another consideration must be given to using a superensemble of hydrologic models based on different precipitation inputs from different global models and/or different parameterizations within the hydrology model itself.

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