Predicting Hurricane Landfall Precipitation: Optimistic and Pessimistic Views from the Symposium on Precipitation Extremes

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One goal of the U.S. Weather Research Program (USWRP; Elsberry and Marks 1999) is to demonstrate the feasibility of numerical guidance that would allow 72-h quantitative precipitation forecasts (QPF) for hurricanes, thereby improving day 3 forecasts for inland flooding. This goal raises serious questions about the predictability limit for tropical cyclone precipitation over the ocean, during landfall, and inland. The goal was thus a motivation for devoting a session of the Symposium on Precipitation Extremes to hurricane landfall precipitation.

If the goal is a deterministic QPF over a small area, such as a watershed for a narrow valley, then some people are rather pessimistic about success. The National Oceanic and Atmospheric Administration (NOAA) National Weather Service Offices and River Forecast Centers issue warnings for flash floods in areas as small as 10–20 mile², or river floods in areas of 1000 mile². Clearly, rainfall has to be resolved on less than 1-mile scales for flash floods, and perhaps 5-mile scales for river floods. Furthermore, the record rainfall rates of tropical cyclones are well known. Given this threat of flooding, what QPF guidance can be offered now, and what is necessary to improve that guidance? The USWRP’s focus on hurricane landfall precipitation has already increased research into this topic. In addition to six invited papers and a wrap-up panel with four invited presenters, 32 posters were accepted for presentation. By contrast, as recently as the 23d Conference on Hurricanes and Tropical Meteorology in 1999, only three papers were presented on this topic. This meeting summary will be a status report on the field, and will address the future requirements that were discussed at the panel session.

**LANDFALL PRECIPITATION CHARACTERISTICS.** A description of some of the precipitation characteristics that must be observed, analyzed, and forecast will help summarize the difficulty of hurricane QPF. Hurricane Research Division aircraft studies were summarized by F. Marks. The eyewall has the greatest variability in updrafts, and high radar reflectivity cores cover only 10% of the rain area, with core areas averaging only 50 km². Radar
reflectivity cores tend to persist on the order of 10 min, so the heaviest precipitation is confined and brief. However, advection of the rain cells tends to create less discrete precipitation patterns over time. Instruments such as radar and high-resolution (1 km) particle probes give aircraft measurements much higher resolution than those from satellites, making averaging over space and time necessary for meaningful comparison. Marks finds that instantaneous rain-rate estimates from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager are $> 20$ mm h$^{-1}$ only within 75 km of tropical cyclone centers; then they decrease rapidly in radius to a relatively flat profile. Given these azimuthally averaged satellite rain rates (and an excellent track), a first-order estimate of the rain accumulation may be provided at points along the track.

A more pessimistic view was evident in some of the other presentations. G. Barnes showed that in Tropical Storm Frances, six distinct regions had 24-h rain totals exceeding 14 in. These regions were not related to the track in any straightforward way. Ward described distinct diurnal variations of rain from Tropical Storm Charley in Texas. The radar reflectivity of this storm as it moved inland had space and time variations typical of a tropical mesoscale convective system (MCS). Corosiero and colleagues attempted to infer the total rainfall distribution of Charley from the lightning. Whereas lightning flashes in the outer rainbands corresponded well with the heaviest precipitation east and northeast of the center, only two of the several precipitation maxima in the core were electrically active.

K. Blackwell and S. Kimball illustrated two very different distributions of maximum rainfall relative to the storm tracks during landfall. Hurricane Georges (1998) had radar-estimated precipitation exceeding 15 in. (381 mm) to the right of the track, as expected from many over-ocean cases. However, the maximum precipitation in Hurricane Danny (1997) was to the left of the landfall point; little precipitation fell to the right. This maximum exceeded 43 in. (1092 mm) according to radar estimates—a gauge measured 36.71 in. (932 mm) as the storm slowly came ashore. R. MacCracken and W. Thiaw described synoptic circulation changes associated with similar extreme tropical cyclone rainfalls that contributed to flooding in Mozambique during February–March 2000.

M. Shuman and colleagues analyzed heavy precipitation from tropical cyclone remnants in the eastern United States during 1989–97 and related these to upslope flow. Konrad studied 48-h precipitation exceeding 1 in. over the eastern United States during 1950–96 on 10 spatial intervals from 2500 to 500 000 km$^{2}$. Hurricane Opal (1995) produced the heaviest rainfall in six of the seven largest intervals. Opal was exceptionally large and interaction with a downstream midlatitude trough produced a moisture inflow that enhanced the rainfall. Slow forward movement contributed to heavy precipitation (just as it did for Tropical Storm Alberto in 1994). No relationships were identified between precipitation amounts and intensity or size of the system.

**EXTRATROPICAL TRANSITION.** P. Harr and R. Elsberry and four others highlighted a new research area on extratropical transition of poleward-moving tropical cyclones throughout the globe. During the transformation stage, the precipitation distribution progressively changes from that of a mature tropical cyclone to a much more asymmetric configuration (maximum generally to the west). As the tropical cyclone remnants reintensify into a baroclinic extratropical cyclone, the precipitation shield expands. Thus, even an offshore system would drop considerable precipitation on the East Coast. Richards and colleagues demonstrated that the extratropical transition of Tropical Storm Harvey (1999) was comparable to a 1:100-yr precipitation event in Nova Scotia and New Brunswick, Canada.

L. Bosart and colleagues distinguished extratropical transitions that interacted significantly with midlatitude troughs and those that progressed poleward into a benign environment. Hurricane Floyd (1999) interacted with a midlatitude trough (potential vorticity anomaly) and subsequently developed a deep, secondary vertical circulation. This circulation concentrated in the jet entrance region with ascent above a strong, deep baroclinic region associated with the coastal front. Bosart et al. suggested that the amount of reintensification is correlated with the low-level warm advection poleward of the storm, the vertical coupling to the equatorward entrance region of a downstream jet streak, and how these processes feed back to release baroclinic energy.

K. Kong’s analysis of the evolution of the coastal front ahead of Hurricane Floyd showed that most of the highest radar reflectivity, and thus precipitation, was just west of the coastal front. Atallah explored how interaction with the midlatitude circulation modulates the precipitation distribution in these cyclones. Warm advection in the lower troposphere and in the hurricane outflow aloft interacts with the midlatitude trough, which enhances the potential vorticity gradients at both levels. The jet streak intensifies and coupling with the tropical cyclone remnants...
increases. Prolonged heavy precipitation north and west of the remnants may ensue.

**FLOODING.** Inland flooding has become the predominant cause of deaths associated with hurricanes in the United States. Because of the absence of coastal mountains, most attention is on regional floods rather than flash floods. G. Austin described Hurricane Floyd (1999) as prototypical: many locations in North Carolina exceeded the 100-yr flood levels. Antecedent conditions played a significant role in this case as Tropical Storm Dennis had slowly moved over eastern North Carolina shortly before Hurricane Floyd approached. The combined precipitation was 24 in. over the Piedmont region. Although these cyclones broke an extended drought, they caused considerable damage. Dams were overtopped or washed out, highways and bridges were flooded, transportation was disrupted, communications were severed, entire towns were inundated, and utilities and energy distribution systems were interrupted. The inundation degraded water quality and damaged fisheries as millions of tons of nutrients, pesticides, and sediments washed into rivers, bays, and the ocean.

Whereas emergency managers would like a precise forecast of flood elevation, this is not possible. First, the precipitation distribution and amounts in the river basin must be known to considerable accuracy. Such a specification is especially difficult if a significant fraction of the precipitation is produced on mesoscale or cumulonimbus scales. If the propagation of these systems opposes the larger-scale advection, the systems may become quasi-stationary and result in extreme, concentrated rainfall that runs off quickly. In addition, antecedent water levels and soil conditions must be specified, and complicating factors such as upstream dam failures, landslides, and debris flows may not be known. Second, present hydrographical models cannot forecast the impact of a river that overflows its banks and spreads. An ensemble approach would provide a probability distribution of the flood elevations, but many people do not understand how to use such probabilities.

J. Lushine has examined flooding in south Florida from 1900 to 1999 and defined five categories of flooding by rainfall amounts, flooding effects, and flooding durations. The categories are provided as forecaster guidance whenever a tropical cyclone approaches south Florida. The categories may help emergency managers and the public understand the flood threat.

The almost 60 deaths associated with Hurricane Floyd were the most for a U.S. hurricane in some time. R. Pielke pointed out that deaths and damages in Floyd were small compared to losses in Central America from Hurricane Mitch, if scaled by respective gross domestic products. Systematic collection of tropical cyclone damages are needed to find out if such losses may be expected to grow. Pielke has considered the growing population in coastal states, increasing wealth, and inflation factors to estimate such trends. Even if a global climate change does not increase the frequency of tropical cyclones, the combined increases in risk from these factors guarantee a probably enormous increase in landfall damage.

Better information is needed to assess the vulnerability of the United States to hurricane landfall precipitation. For instance, Pielke examined Presidential Disaster Declarations caused by flooding and hurricanes. Many inland flooding disasters were delayed consequences of hurricanes. Proper attribution would double the number of hurricane-associated declarations, and frequency of the combined distribution of disasters would correlate well with seasonal tropical cyclone distribution.

**OBSERVATIONS FOR RAINFALL ESTIMATES.** C. Guard and colleagues consider rain gauge accuracy to be critical to the tropical cyclone quantitative precipitation estimation (QPE) problem. First, the radar reflectivity–rain rate (Z–R) relationship is based on a calibration with rain gauges. Second, the satellite radiances or brightness temperatures are also calibrated with these gauges and radar-rain rate estimates. Guard et al. then consider the error sources in tropical cyclone conditions: evaporation, splash, intermittent gauge halt, turbulence and aspiration, reading error, overflow, and wind damage. All except for reading errors likely lead to underestimates of rainfall. The largest error source is likely to be turbulence and aspiration in the high winds (and largest rain rates) under the eyewall. If this causes a 10% loss per 5 m s$^{-1}$ increase in wind speed, and other error sources also contribute, a 50% underestimate of the rain rate under the eyewall may occur. Such a large error during the highest rain rates could lead to a serious calibration error in the Z–R relationship and thus to underestimates in rain rates derived from radar.

Despite the spatial coverage advantage of using a well-calibrated radar, averaging the large rain-rate gradients across the radar range would lead to an underestimate of the largest rain rates. Due to the curvature of the earth, the radar beam beyond 150 km from the radar is often above the region where rain rates are representative of conditions at the ground.

F. Marks noted the relative accuracy of recent rain estimates using the Weather Surveillance Radar-1988
Doppler (WSR-88D) in Hurricane Danny and Hurricane Irene (1999). He noted that recent gauge–radar comparisons are improved for rain rates less than 5 mm h⁻¹, which is encouraging considering the short lifetimes of the rain cells and their rapid translation in a tropical cyclone environment, and that the radar is sampling a volume and the gauge is a point measurement.

A. Cope evaluated the two Z–R relationships available on the WSR-88D as remnants of Hurricane Floyd passed over the New Jersey area. The “tropical” Z–R relation performed better overall than the default Z–R relation through the 12 h of heavy rain prior to passage, except for some overestimation. Significant differences between rainfall totals from two adjacent WSR-88D radars were attributed to differences in distances to the rain, and consequently different radar beam elevations, and perhaps some calibration differences. This study and reports of other rain gauge–WSR 88D comparisons (e.g., by C. Guard) indicate that more research is needed on this topic.

Considering rain gauge measurements are limited to land, and the range of radar rain estimates is perhaps 150 km, satellite measurements provide the only rain estimates in many areas [see Barrett (1999) for more on satellite techniques]. R. Schofield and colleagues summarized satellite-based capabilities for hurricane prediction. The National Environmental Satellite, Data, and Information Service (NESDIS) has modified the Geostationary Operational Environmental Satellite (GOES) hurricane landfall potential technique by substituting microwave rain estimates. This algorithm uses satellite-based microwave rain rates to produce an areal extent of rain and average rain along the direction of motion, which is determined from GOES fixes over 3–6 h. Kidder and colleagues proposed to improve this manual technique by automating it, using official track forecasts instead of extrapolations from GOES fixes, and creating graphical products of accumulated precipitation.

Use of multiple types of instruments seems to be best for QPE. R. Kuligowski and M. Ba propose to improve GOES-based rainfall estimates over land by calibrating the brightness temperature–rain rate relationship with real-time radar and rain gauge data. Their algorithm also includes a rain–no rain separation that compares available predictor fields [auto estimator and GOES Multi-Spectral Rainfall Algorithm (GMSRA)] with the IR brightness temperatures, split-channel differences, and other derived quantities.

J. Turk and colleagues compared the Naval Research Lab (NRL) blended geostationary (GOES) microwave [Special Sensor Microwave Imager (SSM/I)] with the auto estimator and the GSMRRA using hourly digital precipitation estimates from nearly 100 WSR-88D radars. Although their summer test case was not a hurricane, many of their results probably would be applicable. Whereas the auto estimator tended to overestimate the rain associated with high, cold cirrus, the GMSRRA and NRL techniques tended to underestimate the heavy rain pixels that are characteristic of rapidly developing convective systems. The NRL technique separated rain and no-rain regions better because of the microwave data.

Scofield and colleagues also described work with L. Bosart on QPE for landfalls in which precipitation becomes characteristic of an MCS (such as Hurricane Charlie, described earlier). GOES satellite techniques have limited ability to estimate warm-top stratiform rain. Emission-derived rain estimates are the most accurate, but these are presently only available over water. The 150-GHz data from Advanced Microwave Sounding Unit (AMSU) B is expected to improve the warm-top stratiform rain estimates.

In summary, there is cause for both optimism and pessimism about satellite-derived hurricane QPE. Multiple instruments have become available, but each has disadvantages as well as advantages. Because the satellite estimates are on different spatial and temporal scales than aircraft and land-based measurements, it is difficult to calibrate them. Combinations of the various techniques seem to minimize disadvantages and improve the calibrations.

**STATISTICAL AND EMPIRICAL PREDICTIONS.** F. Marks has developed a climatological technique that can be a skill measure for other precipitation prediction techniques. A probability of precipitation might be derived by combining radial distribution information with an ensemble of tracks. R. Pfost checked empirical rain prediction techniques for the northern Gulf of Mexico coast and for the Florida peninsula with a database of maximum rainfall as a function of storm track orientation and shortest distance from the center. Pfost recommended a combination of all methods as the best approach to forecasting the maximum rainfall.

Each of the satellite-based techniques for hurricane QPE is essentially a nowcast, although it is not clear how many hours into the future such estimates may be extrapolated. Averaging these estimates in space and time is required. The accumulation of these satellite (and radar) estimates in time forces the river
streamflow model. Fortunately, regional (versus flash) floods take a day or more to develop, so warnings of 12 h or more are usually possible.

**NUMERICAL WEATHER PREDICTION APPROACHES.** In general, authors were more optimistic about numerical models. F. Marks believed the dynamic constraints, the mixing of hydrometeors around the vortex, and the recent advances in rainfall observing systems will make prediction possible. W. Frank concluded, “Numerical models, augmented by assimilated data, offer real hope for improved forecasts of the amount and distribution of rainfall in landfalling tropical cyclones.” Frank was optimistic about predicting totals because the moisture source—evaporation from the ocean—is fairly well known, except perhaps in the small area of highest winds. While acknowledging that predicting rain distribution is more difficult, Frank believed that new understanding of dynamics and convective asymmetries would lead to better predictions if observations could be properly included in models. G. Tripoli cited similar reasons for optimism and specifically included landfall situations as well as ocean cases, because land surface effects can be predicted by the model. Tripoli had caveats based on microphysical uncertainties and track prediction accuracy. Tripoli’s optimism applied more to research because no U.S. operational forecast center has the computer resources for the necessary cloud-resolving model resolution and physics.

Mountainous terrain close to the coast—such as the Central Mountain Range in Taiwan—contributes to some extreme rainfall amounts. P.-Y. Wang simulated a 269-mm maximum precipitation in 36 h associated with Typhoon Herb in Taiwan with orography included but only 40 mm without it. The maximum (gauge) rain amount was 1997 mm, but this was a point value rather than an average over a 10-km grid box. C.-C. Wu and colleagues also simulated the precipitation associated with Typhoon Herb with various model horizontal resolutions. As expected, the smaller the grid interval, the larger the predicted precipitation. With 2.2-km resolution, the maximum 24-h amount was 1046 mm; with 6.7-km resolution it was 649 mm. Since the maximum rain was simulated to occur just west of the mountain peaks, an accurate forecast of the upslope flow was needed, which meant an accurate track and wind structure. Wu et al. also documented a strong sensitivity to the microphysical representation in the model.

S. Kimball and K. Blackwell attempted to simulate the landfall of Hurricane Danny, which had an anomalous precipitation maximum to the left of the track. Simulations with a 9-km grid did not capture crucial topographic features, and the initial bogus was too large and weak. Thus, finer horizontal resolution and better initial conditions are required. L. White and colleagues focused on the sensitivity of simulations of Hurricane Bert to air–sea interaction since this storm may have been affected by a warm ocean anomaly. R. Abbey and colleagues also suggested that the sea surface temperature anomalies significantly affect tropical cyclogenesis and intensity, and thus precipitation. They used a high-resolution model and concluded that the skill level of QPF at landfall was “encouragingly high.”

M. DeMaria and R. Tuleya have evaluated the 6-h precipitation forecasts by the Geophysical Fluid Dynamics Lab (GFDL) hurricane model during 1995–96. Gridded storm total rainfalls were compared with gauge values and had a lot of scatter. The forecasts had a positive bias (overestimate). The model gives some useful guidance about the storm maximum and area-averaged precipitation, but the geographical distribution may not be accurate.

A crucial caveat in the optimism about hurricane QPF is assimilation accuracy. As G. Barnes emphasized, a large range of circulation scales must be defined in the initial conditions to get the track and the precipitation distribution correct. Given the importance of the surface fluxes of moisture, heat, and momentum in the hurricane boundary layer, these initial variables and upper-ocean thermal structure must also be specified.

G. Panegrossi and colleagues are using the TRMM Microwave Imager and precipitation radar to improve their simulations of precipitation in Hurricane Bonnie (1998). The key issues concern the model’s representation of the sizes and densities of the hydrometeors, which then feed back to the dynamics, the mass of rain at lower levels, and thus to the surface rain rate. Detailed comparisons of the model-predicted precipitation structure to that inferred from the TRMM overpasses seem to require two or more categories of graupel to distinguish between the formation processes in the convective and stratiform regions. Future research will use in situ observations gathered during the National Aeronautics and Space Administration (NASA) Convection and Mesoscale Experiment (CAMEX) to examine these microphysics differences.

M. Tewari and colleagues simulated the precipitation in the Orissa supercyclone (1999) using precipitable water (PW) observations from TRMM and SSM/I. Humidity fields were scaled by the ratio of the observed PW to the model PW and nudged into the model fields over the 24-h prior to the initial time.
This significantly increased the precipitation relative to a control run without these fields, and the track was also predicted better.

E. Ebert used a “poor man’s ensemble” to forecast heavy rain. She collected the predicted fields from seven global and regional models and calculated an ensemble mean. With certain adjustments, the ensemble mean precipitation fields verified better than any of the individual model predictions.

Playing the devil’s advocate to stimulate discussion, this author presented pessimism about deterministic precipitation prediction. Many of the reasons have been noted above and are contained in the caveats to these optimistic views. First, are observations sufficient for providing initial conditions for high-resolution models? Second, can the precipitation and other meteorological variables be assimilated correctly? Given the exponential radial variation of rain outside the eyewall, will track prediction be accurate enough to specify the distribution, duration, and total amount over a small region (a watershed or city)? From the pessimistic view, some space and time averaging will be necessary, or multiple model predictions or an ensemble approach to provide probabilistic precipitation description will be the best guidance available.

**FUTURE REQUIREMENTS.** Starting from the pessimistic viewpoint, the predictability time for deterministic hurricane QPF must be resolved, given that individual convective clouds have predictability times of less than 1 h. F. Marks’s optimistic view is that the eyewall convection and rainbands will be dynamically controlled by the primary wind circulation. However, how well are the boundary layer dynamics and the forcing of convective clouds known for the high winds near the center? Will the forcing from topography degrade or improve the QPF ability? How accurately must the horizontal distribution of the convection be specified to be fully consistent with the dynamical constraints in the model? Several contributors noted that asymmetric convection is critical in QPE and QPF.

W. Frank’s optimistic view is that the large-scale evaporation—the storm’s moisture supply—is fairly well known. Given the small area into which all this moisture converges, heavy precipitation must occur, but will the specific area be well predicted? Why was the extreme precipitation in Hurricane Danny on the left side? Notice that the evaporation and other surface fluxes in the high wind areas are not well known because of the complexity introduced by breaking ocean waves that inject droplets into the air. The U.S. Navy is funding a 5-yr program called Coupled Boundary Layer Air–Sea Transfer (CBLAST), with a major field experiment during 2004. The objective is to measure and better parameterize boundary layer fluxes of moisture, heat, and momentum in hurricanes.

Given model guidance that heavy precipitation will occur somewhere, can forecasters be trained to designate the specific area? Clearly, radar and lightning data (especially in outer regions) help in nowcasting the precipitation area. Evaluations of the model guidance accuracy are needed in a forecaster-friendly format. One suggestion was to develop statistical-dynamical tools or a neural network to give guidance. This approach may be more successful over the ocean than over land, especially when precipitation changes to MCS-type characteristics that are under less dynamic control of the hurricane remnant circulation.

The interaction of the hurricane remnants with a midlatitude trough or front adds further complexity. As several contributors noted, the precipitation in advance of Hurricane Floyd in conjunction with a coastal front and warm advection contributed to flooding. Since, in extratropical transition, midlatitude troughs and jet streaks are moving eastward and tropical cyclones are moving poleward, the timing of the juxtaposition of these systems is difficult to forecast. As P. Harr and R. Elsberry note, the vertical wind shear of the midlatitude circulation affects the tropical cyclone, and the warm advection and outflow of the tropical cyclone may modify the midlatitude cyclogenesis. In situ observations of these processes are needed.

Satellite data are critical for analyzing initial conditions. Scofield and colleagues stated future needs: 1) improved ground truth measurements (gauge and radar) and validation methodology; 2) improved physical understanding of satellite measurements in relation to precipitation, and optimum ways to combine these measurements along with radar and rain gauge values; and 3) appropriate forecaster displays of instantaneous or probabilistic amounts. Higher-resolution passive microwave sensors are needed to better resolve the precipitation gradients. Techniques to assimilate these satellite observations into numerical models need to be developed and tested. Will the four-dimensional variational assimilation techniques provide an incremental improvement via the incorporation of the time dependency in these datasets?

G. Barnes and G. Tripoli emphasized that the vital precipitation physics must be known better. Barnes distinguished between the convective available potential energy (CAPE) of the external rainbands and of the eyewall region. Corbosiero and
colleagues have inferred this difference in convection characteristics from lightning distributions, but quantitative information is needed for the model initial conditions.

The microphysics of clouds impacts the radiative transfer relationships needed for satellite estimation. Again, in situ observations are required for calibration. As the horizontal resolution of the models has improved enough to explicitly resolve clouds, microphysics parameterizations have become a major source of uncertainty in the models. The field programs should be combined with numerical simulations to demonstrate that better microphysical representation will improve QPF. Operational implementation will require providing the model with initial microphysics variables.

Radar data from NOAA research aircraft provide information on the storm structure and precipitation while the cyclone is still outside of land-based radar range. This information needs to be incorporated in the models. When the hurricane is within range of the coastal WSR-88Ds, assimilation techniques are required to use the radar reflectivity and radial wind components. From an operational perspective, additional research on the WSR-88D Z–R relationship is needed and forecasters need to know how to properly infer rainfall in tropical cyclones at various distances from the radar.

Hydrological aspects of flooding must also be addressed. G. Austin listed a number of requirements for improved flood warnings: 1) more accurate hurricane track forecasts; 2) improved QPEs in terms of timing, location, and amounts; 3) more river stage data; 4) more accurate, specific, and timely hydrological forecasts that are easier to use, specify uncertainty, and extend to longer intervals; and 5) better education on how to interpret and use these forecasts. Better display of the information is needed. A useful product would display how widespread the floodwaters will be. Better integration with flood prediction management would also be helpful.

Improved meteorological and hydrological warnings will fail, however, if the public does not respond properly to the threat. Given the importance of inland flooding in U.S. hurricanes, R. Pielke recommends updating flood plans. They should be dynamic because social changes must be incorporated. Decadal variations in hurricane occurrence may also be a factor in assessing the changing vulnerability. Flooding along highways must be specified because many deaths occur when people drive into floodwaters. Education of the public and the media about hurricane flooding must be pursued vigorously. Attention must continue to focus on the threat from a hurricane after it crosses the coast.

REFERENCES

