n a time scale
ronments: The
d *interspecies*
Melia, and J.J.
Layer structures
996: Simulation
sional physical-
J. Unluata, 1999:
ling in the Black
distinct vertical
Oxic, Suboxic and
g the response of
agic food web. *J.*
cross the suboxic-
toplankton seasonal
Black Sea example.
Mesoscale Processes
m SeaWIFS-derived
sity values as a label
ciasu, and D. Ediger,
rophyll-a in the Black
ool for the Black Sea.
ds., Kluwer Academic

Development of the Regional Forecasting System for the Black Sea

Şükrü T. Beşiktepe

sukru@ims.metu.edu.tr
Institute of Marine Sciences, Middle East Technical University,P.O. 28, Erdemli, İçel 33731 Turkey

Abstract- Black Sea Forecasting System to predict the physical and biogeochemical variabilities of the Black Sea have been developed within the context of the NATO SfP-ODBMS Black Sea project. The system consists of 3-d physical and biochemical models and assimilation scheme. The system has been calibrated and validated and prepared ready for real-time applications.

Introduction

The primary objective of the present research effort within the NATO SfP ODBMS Black Sea project was to develop a ocean forecating system to predict the ecosystem variabilities of the Black Sea. The developed system will allow prediction of future states of the sea (forecasting); descriptions of the present (nowcasting) and, the past states of the sea (hindcasting).

There are three stages in the development of a regional forecast capability involving exploratory, dynamical and predictive phases (Robinson, 1996). Determining features and processes existing in the Black Sea forms the exploratory phase, leading to constructing the model framework and geometry. Dynamical phase involves the calibration of the model through the determination of synoptical dynamical events and interactions, and the elucidation of dynamical processes governing mesoscale evolution and sub-mesoscale events. Calibration and validation of the model is done at this phase. The forecast studies are done at the predictive phase.

This 3-phase strategy has been considered in the development of Black Sea forecast system. In this paper we present the overall view of the model calibration and validation studies.

Interdisciplinary model system

The Harvard Ocean Prediction System was used to carry out the data driven simulations of physical-biogeochemical variabilities. The system consists of coupled dynamical models, statistical models, initialization procedures, data assimilation schemes, and various visualization and post-processing tools (Fig. 1). HOPS is a flexible, portable and generic system for interdisciplinary nowcasting, forecasting and data-driven simulations at sea (Robinson, 1996, Lozano et al., 1996, Robinson, 1999). It has been successfully applied to different regions including real-time shipboard forecast experiments with validation and verification of forecast skill (Robinson et al.,1996, Lermusiaux and Robinson, 2001).

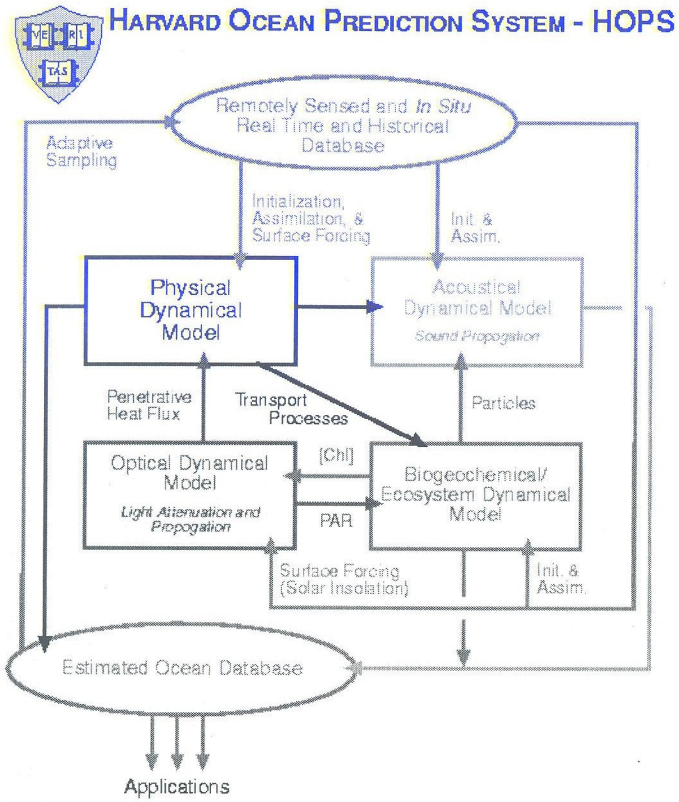

Fig. 1. Schematic of the Harvard Ocean Prediction System

The physical dynamical model employed here is the four-dimensional primitive equation (PE) model of HOPS, which is based on the GFDL integration algorithm. The PE model includes terrain following coordinates and algorithms designed for accurate estimates of pressure gradients in steep and/or shallow topography. Horizontal subgridscale processes are parameterized using a Shapiro filter, which is applied on the sub-mesoscale component of the total PE fields. The bulk vertical diffusion is a Richardson number dependent parameterization. The transfer of atmospheric fluxes to the water-column involves a vertical mixing-length turbulent model based on a locally computed Ekman depth. A bottom boundary layer and coastal friction parameterizations are also incorporated.

The biogeochemical model coupled to the physical model includes phytoplankton, zooplankton, detritus, nitrate, ammonium and chlorophyll-a (Fig. 2). The explicit modeling of chlorophyll-a is important as it allows the relatively direct use of satellite images (sea-surface-color) and in situ fluorometer profiles for

model validation and data assimilation. In the model, fluxes and state variables are expressed in terms of nitrogen. The details of the biogeochemical model can be found in Beşiktepe et al., 2003. The biogeochemical model parameters used by Oğuz et al., 1999 is used in the present study.

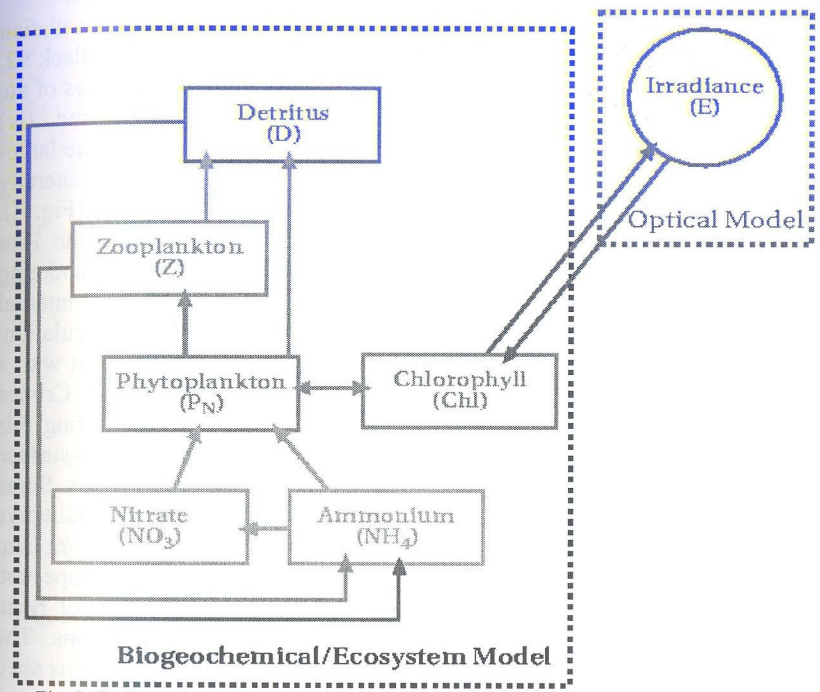

Fig. 2. Scehematic of the biogeochemical model used.

Data assimilation strategies in a forecast system provide the means for model initialization and update, melding model fields and primary data, tuning of model parameters, and providing error estimates. Presently, the Optimal Interpolation (OI) scheme of HOPS is employed to assimilate the synoptic data in the ecosystem simulations. The data-forecast melding step of this OI scheme consists of a two-scale Objective Analysis (OA) of the observations, followed by a blending of the forecast with the OA fields.

Black Sea Forecasting System

The coupled physical/ecosystem model domain covers the entire Black Sea at a resolution of 9 km in latitude and longitude. The size of the resulting horizontal grid is 130 by 74 grid points. The model uses 28 non-uniformly spaced depth levels and realistic bottom topography. The bathymetry was obtained from digitized database of the IOC charts and interpolated to model grid. A second order Shapiro filter applied 4 times to smooth out steep topographic features to minimize the error associated with the sigma coordinate system. Sensitivity parameter studies aid in the understanding of artificial effects of the topography on circulation. For the smoothed topography the spurious current withthe magnitude of 1 cm/s is produced at the end of 30 days of model integration which ensure that there is no significant error due to pressure gradient computations on sigma coordinates.

As a first step, evolution of the basin-wide temperature, salinity and circulation is studied. The data from (i) a basin-wide hydrographic survey, CoMSBlack'92, obtained in the Summer of 1992; (ii) wind stress derived from wind analyses of the Sevastopol MSIA/URHI Office; (iii) climatological heat fluxes; and (iv) climatological river outflows are used to initialize and force the model. The large-scale upper layer circulation over the deep portion of the basin is generally cyclonic with a system of anticyclonic eddies evolving in its periphery (Fig. 3). The edge of the cyclonic circulation is dominated by an inertial jet: the Rim Current. As the Rim Current transverses the edge of the deep basin, the meandering and secondary circulation associated to the jet varies according to internal dynamics and interactions with the bottom topography and shelf water circulation. The relatively broad northwestern shelf is found to be mostly wind driven with a buoyancy-driven coastal current and interacting with the quasi-stationary Crimea and Kaliakra anticyclones. The seasonal thermocline is strengthened during this period and a zonal large-scale temperature gradient with warmer/colder sea-surface temperatures in the east/west is driven by the observed weak/strong winds. Some of the major circulation elements are partially verified using qualitative comparisons with the Summer of 1992 data and historical data; both *in situ,* and infrared and color remotely sensed data. The Rim Current meander shape and propagation parameters, eddy size and distribution, and the generation of rapid surface bound jets are found to be in good agreement with observations. The simulation shows two previously unobserved events: an anticyclonic eddy is shed near Sinop; and the anticyclones moving north along the Caucasian coast are formed and shed from the Batumi eddy. Imprints of these events are found in the historical record. Details of this study can be found in Beşiktepe et al., 2001.

The synoptic basin scale biogeochemical data was not available. Instead, the biogeochemical data were generally collected in a limited area within the basin. Due to this limitation,we applied the coupled model to the areas where the data was available. We will present the results from two case studies below using the data from two different cruises.

May-June 2001

The model grid covers the southwestern Black Sea at a resolution of 4.5 km with 28 levels in the vertical (Fig. 4). The other modeling issues related to application of the HOPS to the Black Sea is the same as in Beşiktepe et al., 2001 except the open boundaries in the present study. At open boundaries, conditions based on an Orlanski radiation scheme are employed.

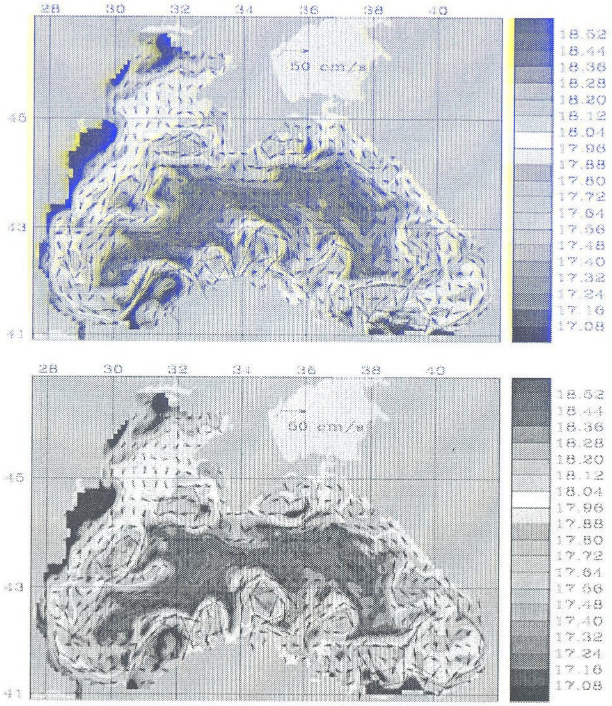

Fig. 3. Model predicted velocities overlapped on sali ity distribution at surface at day 45 and 50

Data driven simulations in the Black Sea based upon these observations and a coupled 3-d physical and biochemical models have been carried out. The model initialized using physical, chemical and biological data collected during the first leg of the survey. Model forced with QuickSCAT Level 3 Daily wind fields. Physical and biological data collected during second leg were assimilated to the model. The model results with and without biological data assimilation were compared.

A time-line of these initialization steps and subsequent data assimilations is given on Fig. 2.The initial physical fields are computed for May 25, using the OAs of the initial T, S data, geostrophy and an imposed barotropic transport streamfunction along open-boundaries. Chlorophyll-a, nitrate, ammonium fields were computed by objective analyses of observed data. The remaining biological fields (phytoplankton, zooplankton and detritus) were derived from objectively analyzed data chlorophyll data. Phytoplankton biomass in terms of nitrogen was computed from chlorophyll-a using carbon to chlorophyll and carbon to nitrogen ratios for the region. Zooplankton and detritus biomasses were taken as a fractions of the phytoplankton biomass.

Along the course of the simulation MODIS chlorophyll and AVHRR SST measurements assimilated to the model.Validation of the physical model were done using the ADCP data collected on board R/V Knorr in the area at May 29 and the validation of the biogeochemical model forecasts were don on June 17.

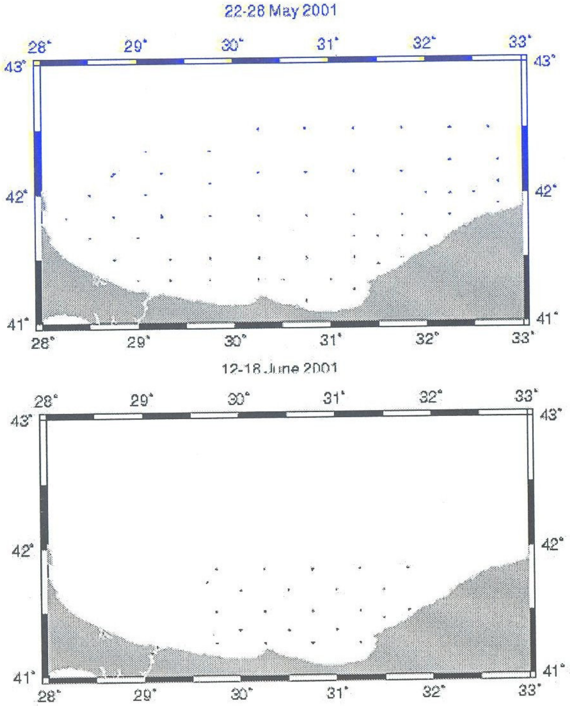

Fig. 4. The positions of the hydrographic stations which were used to initialize the model (upper panel) and to assimilate to the model (lower panel).

The distributions of nitrate, zooplankton, chlorophyll-a and new production at initialization are given in Fig. 5. Nutrient concentrations are generally low in the surface waters except at the north-western corner of the region whre river waters intrudes. The chlorophyll-a concentrations are higher near the coastline and follows the structure of the rim current. Zooplankton distribution follows the chlorophyll-a distribution as expected. Because zooplankton concentrations were calculated from chlorophyll-a concentrations as explained above. The distributions explained above are display typical autumn conditions for the Black Sea and it is seen that the features in the study region are mainly the result of a sustained advection of the river originated nutrient rich waters from the north-western part of the basin into the study area.

By day 25 (Fig. 6), the distributions of the biogeochemical constitutes are the result of the redistribution of the nutrient and biomass rich coastal waters in the

region by the rim current. The local uptake of nitrate by phytoplankton as a proxy for new production indicates that the new production occures only on the rim current. As is characteristic of late summer conditions,the new production is low and does not follow the detailed structure of Chl-a. The phytoplankton biomass is indeed sustained by the ammonium production rate (not shown. However the production in Autumn 2001 is very low as compared to other yers in the Black Sea.

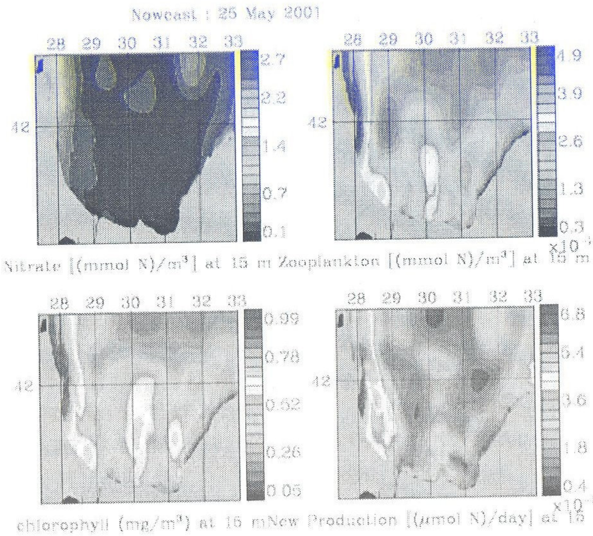

Fig. 5. Distribution of nitrate and chlorophyll-a (from measurements) and zooplankton and new production (calculated) at initialization.

October 2000

The oceanographic survey with mesoscale grid resolution was conducted in the eastern Black Sea during October 2000 to investigate spatial variability of zooplankton and its relationship to physical and biogeochemical variabilities. The data set collected during the cruise consists of temperature, salinity, PAR, TSS, nutrients, chlorophyll-a and zooplankton size classes. The distributions of the model initializations fields obtained from observations are presented in Fig. 7.

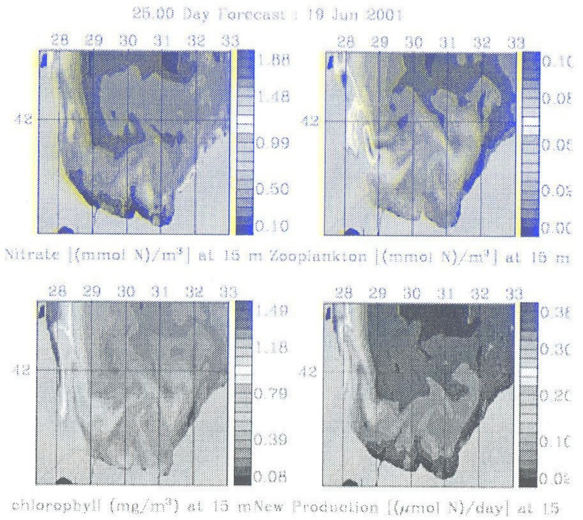

Fig. 6. As in Fig. 4, but for day 25

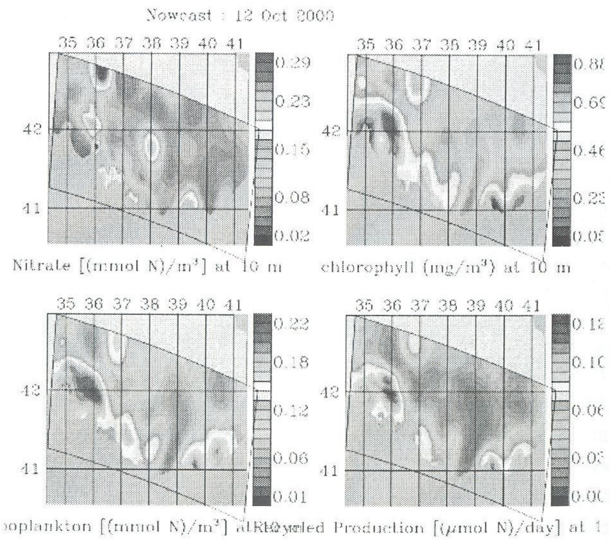

Fig. 7. Model initialization fields.

The large-scale upper layer circulation over the deep portion of the basin is generally cyclonic with a system of anticyclonic eddies evolving in its periphery. The edge of the cyclonic circulation is dominated by an internal jet: the Rim Current. The rim current were experiencing a ridge upon entering the study area and series of eddies were forming downstream of the ridge. The Rim current was dividing the study area into three regions by means of their physical, chemical and biological properties; the coastal waters, the Rim current waters and open sea waters. In spite of the rivers discharging to the coastal waters, the concentrations of the biogeochemical variables were higher in the Rim Current region. This is mainly because the Rim Current carries nutrient rich river waters originated from the northwestern region and the biological production is high on this water. Zooplankton were mainly advected to the region with the rim current. The presence of the anticyclonic eddy between the Rim Current and the coast were entrapping the zooplanton as wel as the other biogeochemical variables. Hence, the phytoplankton and zooplankton were reaching to their maximums in this anticyclonic eddy (Fig. 8).

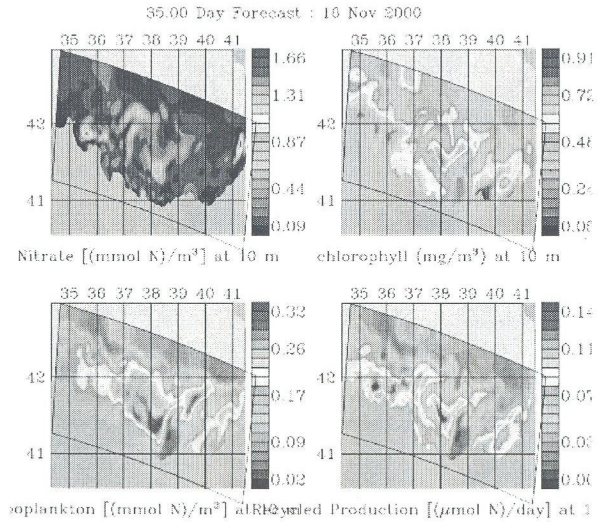

Fig. 8. Model predicted fields at day 35.

Conclusion

This work was a contribution to the development of a physical, chemical and biological regional forecast system for the Black Sea. The developed, calibrated and validated model within the context of this study will be used in the operational observation and prediction system for the region.

The results show that the model is able to generate and maintain the 3-d structures of the physical and biogeochemical fields. Model results are partially validated using observations. The size, structure and evolution of the main currents and eddies in simulation compare favorably to in situ observations and remotely sensed satellite measurements.

Acknowledgements- *The support to cruise came from projects entitled Biogeochemical cycles in the Black Sea, Marmara Sea, Aegean Sea and the Mediterranean, which was supported, by Turkish Scientific and Technical Research Council and the NATO-SfP Black Sea Ecosystem Processes And Forecasting / Operational Database Management System project. The work supported by NSF and TUBITAK through the joint NSF-TUBITAK program.*

References

Beşiktepe, Ş, C.J. Lozano and A. R. Robinson (2001) On the Summer Mesoscale Variability of the Black Sea, *Journal of Marine Research,* **59**(4):475-515.

Beşiktepe, Ş. T., P. F. J. Lermusiaux, A. R. Robinson (2003) Coupled physical and biochemical data driven simulations of Massachusetts Bay in late summer: real-time forecast and data assimilation, *Journal of Marine Systems,* **40-41**, 171-212.

Lermusiaux, P.F.J. and A.R. Robinson, 2001 Features of Dominant Mesoscale Variability, Circulation Patterns and Dynamics in the Strait of Sicily. *Deep-Sea Research I,* **48**, 1953-1997.

Lozano, C.J., A.R. Robinson, H.G. Arango, A. Gangopadhyay, N.Q. Sloan, P.J. Haley, Jr. and W.G. Leslie, 1996, An Interdisciplinary Ocean Prediction System: Assimilation Strategies and Structured Data Models. *Modern Approaches to Data Assimilation in Ocean Modelling* P. Malanotte-Rizzoli, Ed., Elsevier Oceanography Series, Elsevier Science, The Netherlands. 413-452.

Oğuz, T., H. Ducklow, P. Malanotte-Rizzoli, J.Rizzoli, J.W. Murray V.I. Vedernikov, U. Unluata, 1999, A physical-biochemical model of plankton productivity and nitrogen cycling in the Black Sea. Deep Sea Research I, **46**, 597-636.

Robinson, A.R., 1996, Physical processes, field estimation and an approach to interdisciplinary ocean modeling, Earth-Science Reviews,**39**,3-54}

Robinson, A.R., H.G. Arango, A.J. Miller, A. Warn-Varnas, P.-M. Poulain and W.G. Leslie, 1996, Real-Time Operational Forecasting on Shipboard of the Iceland-Faeroe Frontal Variability. *Bulletin of the American Meteorological Society,* **77**(2), 243-259.

Robinson, A. R, 1999, Forecasting and Simulating Coastal Ocean Processes and Variabilities with the Harvard Ocean Prediction System. In Coastal Ocean Prediction, Ed, C. N. K. Mooers, American Geophysical Union, Washington DC, 77-100.

Robinson, A.R., P.F.J. Lermusiaux, P.J. Haley, Jr. and W.G. Leslie, 2002, Predictive Skill, Predictive Capability and Predictability in Ocean Forecasting. *Proceedings of Oceans 2002 IEEE/MITS Conference*, 787-794.