A Prototype Fully Coupled Ocean-Atmosphere Prediction System

By Thomas E. Rosmond

Coupling of the Navy's atmosphere and ocean prediction models has a natural place in the Navy's research mission and is a major goal of meteorologists and oceanographers in the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) during the 1990s. Navy atmospheric models have been providing valuable support to Navy operations for many years, and computer power now has made operational ocean prediction models feasible.

The challenges of successfully coupling atmosphere and ocean models are great. Coupled systems must accurately predict air/sea interface conditions, e.g., sea-surface temperature (SST) and surface fluxes, whereas uncoupled atmosphere and ocean models depend on prescribed interface conditions. The extra degrees of freedom at the interface in the coupled systems may be a theoretical advantage for realistic simulation of atmosphere/ocean exchanges, but the lack of any constraints at the interface also can allow unacceptable systematic errors, e.g., SST biases. The goal of NOARL atmosphere and ocean modelers is to design atmosphere and ocean models that can exploit the advantages of coupling without the systematic errors.

For many years, there has been general consensus among meteorologists and oceanographers that two-way interactive coupling should be the best way to model the interactions between the atmosphere and ocean. Early research efforts such as Manabe *et al.* (1975) and more recently Manabe and Wetherald (1986) concentrate on longer-term climate-time-scale simulations, where atmosphere-ocean interaction is a dominant factor determining the behavior of both the atmosphere and ocean components of the coupled system. Even these efforts restrict the coupling to a simplified ocean mixed-layer model underneath an atmospheric general circulation model (AGCM). Experiments with a fully coupled AGCM and three-dimensional ocean general circulation model (OGCM) have been limited, but some early attempts have been made (e.g., Washington and Meehl, 1989; Stouffer *et al.*, 1989). Fully coupled experiments for the shorter time scales (5–10 days) of traditional numerical weather prediction (NWP) or even extended prediction (30 days) are now getting scientific attention. Experiments on the sensitivity of NWP models to SST anomalies suggest that even after 10 days, air/sea interaction effects are still minor compared with other physical processes in the free atmosphere (Ranelli *et al.*, 1985). Therefore even a perfectly interacting atmosphere/ocean model will probably show little positive benefit for the atmospheric part of the forecast. The benefit to the ocean part of the forecast, specifically the ocean mixed layer, has not been studied, however, and cannot be ignored in determining potential benefits and research priorities for fully coupled models.

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The coupled Navy Operational Global Atmospheric Prediction System/Thermodynamic Oceanographic Prediction System (NOGAPS/TOPS) is the Navy's first effort at joining an AGCM/NWP model and an ocean mixed-layer model such as TOPS. The choice of NOGAPS and TOPS is a clear one because each is a well-established operational system in its own right, and there is abundant expertise available for both at NOARL and Fleet Numerical Oceanography Center (FNOC). The documented performance records of each of the operational systems also provide excellent control data for coupled system evaluation and validation.

The Coupling Problem

Atmosphere/ocean systems coupling strategies are of two types.

Asynchronous or Loosely Coupled

The two models of the system run in sequence, each model getting forecast time-series forcing fields from a previously run sequence of the other model. Typically the atmospheric model is run for a 24-hour forecast with a fixed SST as the bottom boundary condition. The ocean model then runs for this same 24 hours being forced by the time series (e.g., every 3 hours) of surface fluxes

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generated by the atmospheric model over the period. At the end of the 24 hours, the ocean model has predicted a new SST, and the atmospheric model can begin another cycle.

Synchronous or Tightly Coupled

The two models are integrated in lockstep, exchanging the SST and surface flux information at the same grid points for every model time step. There is now only one combined model, the interactions across the air/sea interface being modeled in more detail than in the loosely coupled case.

Another serious problem with coupled atmosphere/ocean models is the development of large systematic errors . . .

Readers may feel that there is little fundamental difference between these two approaches, only a different time step separating exchange of information across the air/sea interface. Logistically, however, the loosely coupled system is more easily controlled because the exchange of parameters across the models' air/sea interface is independent of the time integration processes of the models. Typically the parameters are stored in a data base where they can be subjected to filtering, various kinds of quality control, and other reality checks before being passed to the appropriate model component. Figure 1 shows the asynchronously coupled system of NOGAPS and TOPS currently run operationally by FNOC. The combined systems do four-dimensional data assimilation for

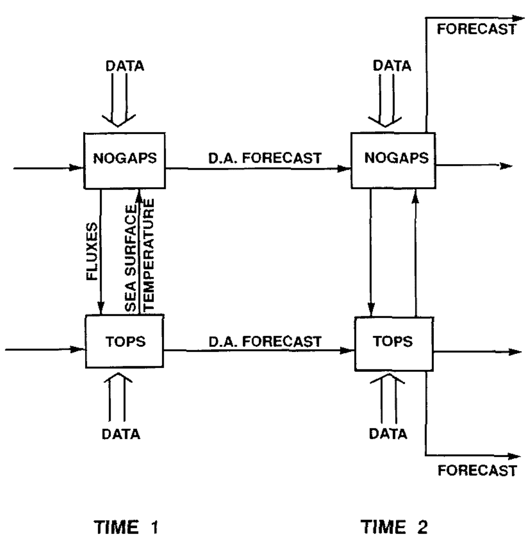

Fig. 1: The loosely coupled atmosphere/ocean data assimilation (D.A.) system of NOGAPS and TOPS currently runs operationally at Fleet Numerical Oceanography Center. The horizontal arrows between the boxes are the short D.A. forecasts; the arrows at the upper and lower right corners are longer forecasts. For simplicity the D.A. forecasts are shown to be the same length in both NOGAPS and TOPS, typically however, a TOPS D.A. forecast is 24 hours and a NOGAPS D.A. forecast is 6 hours.

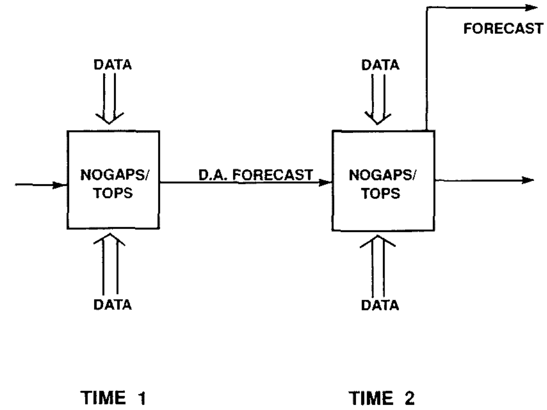

Fig. 2: The fully coupled (synchronous) NOGAPS/TOPS system. The boxes represent analysis times, when observations from both the atmosphere and ocean are assimilated. The arrows between boxes are the short data assimilation (D.A.) forecasts, and the arrow on the upper right is a longer forecast periodically spun off.

both the atmosphere and ocean. The interval between oceanic data insertion is 24 hours and for atmospheric data is 6 hours. The TOPS SSTs and NOGAPS surface fluxes are subject to climatological adjustments to prevent large biases from developing in the models' forecasts.

The fully coupled NOGAPS/TOPS that is the subject of this report is an example of a synchronously coupled system. Figure 2 shows the intimate relationship of the two models, and Figure 3 demonstrates the vertical layer structure on each side of the air/sea interface. The TOPS SST is fed to NOGAPS and the NOGAPS fluxes of momentum, sensible heat, latent heat (evaporation), and precipitation are fed back to TOPS. Instead of a data-base interface between the two models, all exchange of these parameters is done internal to the models through the memory of the host computer system. The ability to apply quality control and other constraints is limited compared with the loosely coupled case (Fig. 1). Furthermore, the short time interval of parameter exchange (typically 15- to 20-minute steps) sometimes allows the development of spurious high-frequency solution modes (e.g., high-amplitude inertial oscillations) that are difficult to eliminate and can contaminate physically realistic solutions. The many hours between parameter exchange and data insertion in the loosely coupled system effectively filter high-frequency modes and prevent this contamination.

Another serious problem with coupled atmosphere/ocean models is the development of large systematic errors or biases in the models' solutions. These errors are often called "climate drift" and are common to all AGCMs, whether coupled to ocean models or not. For coupled models, systematic errors in AGCM surface fluxes are most critical. As mentioned above, the loosely coupled operational NOGAPS/TOPS depends upon climatological constraints on the surface fluxes to prevent the predicted SST from developing large biases in areas where NOGAPS fluxes are in error. NOGAPS surface-flux systematic errors, although no worse than those of other major AGCMs, are still too large to allow unconstrained air/sea interactions. In fact, no AGCM is yet good enough to satisfy this demand (Schneider, 1990). The great challenge for fully coupled NOGAPS/TOPS research and development is to reduce surface-flux systematic error so that such adjustments are unnecessary.

Both loosely coupled and tightly coupled atmosphere/ocean model systems have important roles to play in the design of future Navy prediction systems. Operational-coupled AGCM/OGCMs will probably be loosely coupled, because of the large difference in time and space scales of interest. The baroclinic eddies and current systems in the ocean have time scales of order weeks and space scales of order 100 km; comparable scales in the atmosphere are days and 1,000 km. For these time and space scales, all interaction of interest takes place over the time scales that are well resolved by the data insertion interval of four-dimensional data assimilation (12/24 hours). However, fully coupled AGCM/OGCMs certainly do have a place for seasonal and multiple-year model integrations. Simulating the subtle interactions between atmosphere and ocean that are of such great importance for questions of global climate change may only be captured by a closely coupled AGCM/OGCM. In the future, such a model will be an important part of the Navy's research on air/sea interaction and model systematic error reduction.

On the other hand, tightly coupled AGCMs and ocean mixed-layer models, such as NOGAPS/TOPS, are appropriate because the important time and space scales of the atmosphere and ocean mixed-layer are quite comparable. Surface fluxes drive the mixed layer, and responses in the form of mixed-layer deepening and inertial oscillations can occur within hours after the passage of intense cyclones and frontal systems. Only a tightly coupled system can faithfully capture these kinds of interactions.

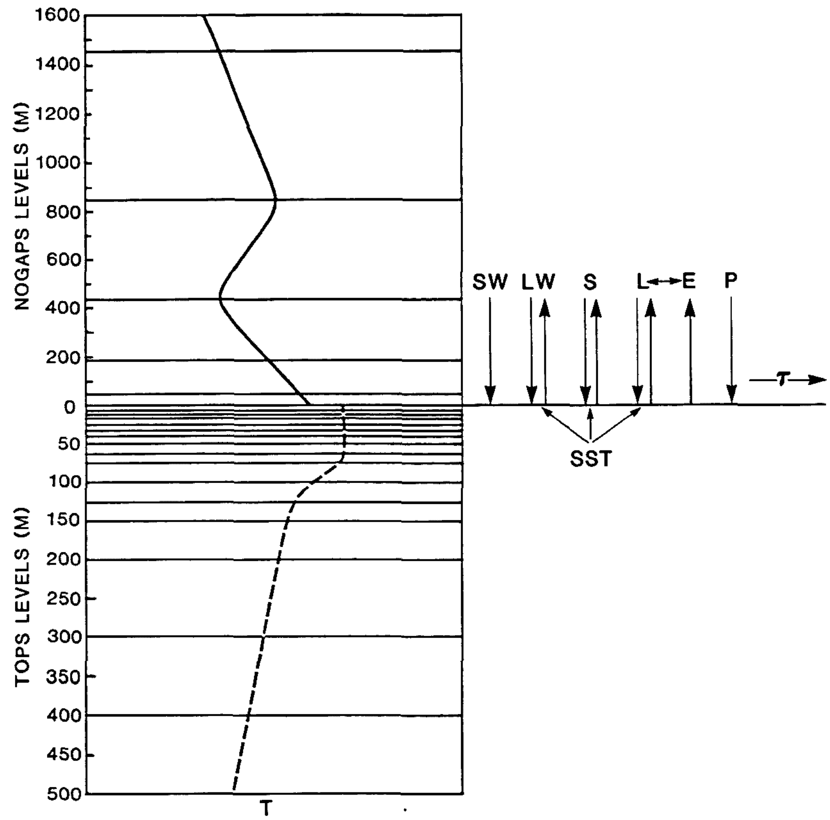

Fig. 3: The vertical structure of the coupled NOGAPS/TOPS system. Exchanges of sea-surface temperature and the fluxes of heat [sensible (S), latent (L), shortwave (SW), and longwave (LW) radiation], moisture evaporation (E) and precipitation (P), and friction (τ) take place at the air/sea interface. Idealized profiles of temperature (T) in the planetary boundary layer and mixed layer are shown. Note that the vertical scales on each side of the interface are not the same.

Description of Navy Operational Global Atmospheric Prediction System

The NOGAPS forecast model is a highly sophisticated AGCM, similar in design and performance to the NWP models run operationally at the European Centre for Medium-Range Weather Forecasts (ECMWF) and at the National Meteorological Center (NMC). A description of NOGAPS and a summary of operational performance is given by Hogan and Rosmond (1991). More details of the NOGAPS spectral forecast model are given in Hogan *et al.* (1991). Only a brief summary will be given here.

NOGAPS is actually much more than a forecast model. It is a complete atmospheric forecast system, capable of assimilating atmospheric observations of all types, including satellite data, and capable of producing a wide variety of physical parameters used in all of FNOC's applications supporting fleet operations. NOGAPS checks all observations with elaborate objective quality control (Baker, 1991) before using these data in a global optimum-interpolation objective analysis (Barker *et al.*, 1988). Undesirable gravity waves are filtered from the analysis fields with nonlinear normal-mode initialization (Hogan *et al.*, 1991). The NOGAPS forecast model is spectral, with an operational horizontal resolution of 1.5 deg and 18 vertical layers from the surface to 10 millibars. The model contains the physical processes of the planetary boundary layer (PBL), gravity-wave drag, cumulus convection, stable precipitation,

NOGAPS [Navy Operational Global Atmospheric Prediction System] is . . . a complete atmospheric forecast system . . .

short- and longwave radiation, and ground hydrology.

Every component of a system like NOGAPS is important because there are complex interactions taking place among all physical processes, just as in the real atmosphere. However, for the coupling problem there are special areas of emphasis.

PBL Parameterization

This computes the surface fluxes that ultimately drive TOPS. The NOGAPS PBL is similar to that used by ECMWF (Louis *et al.*, 1982). An important NOGAPS modification to the basic PBL parameterization scheme is a shallow cumulus (e.g., trade-wind cumulus) parameterization that enhances surface fluxes when the PBL is conditionally unstable.

Cumulus Parameterization

This is based on the Arakawa-Schubert scheme (Hogan *et al.*, 1991). In the tropics the interaction of cumulus convection with the PBL is the dominant factor in determining surface-flux distributions. No AGCM can predict realistic surface fluxes unless cumulus/PBL interactions are adequately simulated. Great effort has gone into the design and "tuning" of the NOGAPS cumulus and PBL parameterizations to achieve this.

Radiation/Cloud Interactions

This is probably the single most important factor in determining AGCM systematic error properties. Sensitivity experiments with NOGAPS have demonstrated that interaction of solar and infrared radiation with clouds dominates the global heat budget. The vertical distribution of radiative heating determines atmospheric stability and therefore the distribution and intensity of cumulus convection, which in turn interacts with the PBL to influence the surface fluxes. Success in coupled atmosphere/ocean modeling, and specifically the coupled NOGAPS/TOPS, will largely depend on proper representation of the global cloud field and its interaction with the NOGAPS radiation parameterizations. For a description of the NOGAPS radiation see Hogan *et al.* (1991).

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No significant changes are made to the formulation of the operational version of NOGAPS for the coupled NOGAPS/TOPS configuration. However, TOPS computer memory requirements added to operational NOGAPS requirements exceed the limits of the FNOC computer system, so the coupled NOGAPS/TOPS is run with a 20% reduction in horizontal resolution compared with the operational NOGAPS.

The only manifestation of the interaction with the ocean mixed layer is the time-dependent SST instead of the time-invariant SST normally used when NOGAPS is run operationally. In NOGAPS, the SST is carried as part of the global surface temperature field. This is already a predicted quantity for land areas, so it is trivial to allow the SST to vary also.

Description of Thermodynamic Ocean Prediction System

Clancy and Pollak (1983) describe TOPS, the ocean mixed-layer component of the coupled NOGAPS/TOPS system. The operational TOPS runs daily at FNOC as part of a global ocean data assimilation and forecast system. TOPS itself is only the forecast component; the Optimum Thermal Interpolation System (OTIS), described by Clancy *et al.* (1990), is the analysis component. SST, mixed-layer thickness, and vertical density profiles are among the parameters produced by the TOPS/OTIS-based system. OTIS is external to the coupled NOGAPS/TOPS, as is the equivalent atmospheric analysis component (Barker *et al.*, 1988), and so is not discussed here.

TOPS is based on the higher-order turbulence closure theory following Mellor and Yamada (1974). The operational TOPS corresponds to a level-2 closure in the Mellor/Yamada hierarchy. In this closure, a local balance between generation and dissipation of turbulent kinetic energy (TKE) is assumed. From this balanced TKE distribution, eddy mixing coefficients are derived, allowing the computation of vertical turbulent mixing in the mixed layer.

The governing equations of TOPS predict vertical mixing of heat and salinity and also the Ekman component of the horizontal momentum field. There is no explicit modeling of the geostrophic component of the momentum. This must be externally specified from climatological sources or, eventually, from a loosely coupled OGCM.

Some modifications of the original operational TOPS are made for the coupled NOGAPS/TOPS version.

1. The TOPS forecast grid is modified to correspond to the global latitude/longitude grid of NOGAPS; the operational TOPS runs on separate polar stereographic forecast grids for the northern and southern hemispheres.
2. The model runs as a set of FORTRAN subroutines called by NOGAPS, rather than as a stand-alone program. This allows the easy exchange of SST and surface fluxes across the air/sea interface of the two model components.
3. The assumption of balance between production and dissipation of TKE is relaxed in the coupled NOGAPS/TOPS. Numerical experiments show that for intense, rapidly moving atmospheric frontal systems, production of TKE in the mixed layer is significantly greater than dissipation for a few hours in the areas directly influenced by the front. An implicit time-integration scheme allows an imbalance to exist when surface forcing is strong, but quickly returns the mixed

layer to a balance when the transient forcing passes. Numerical problems such as spurious high-amplitude inertial oscillations are suppressed by this TOPS modification.

Fully Coupled Model Results

The coupled NOGAPS/TOPS has been run for several 10-day forecast case studies and some 30-day extended forecast experiments. A comprehensive discussion of research results is beyond the scope of this report. The following observations summarize the coupled system's performance.

1. A general SST cooling bias over the winter-hemisphere ocean basins is observed. SST cooling biases also occur in some tropical regions.
2. Global mean sensible and latent heat fluxes between the atmosphere and ocean are systematically reduced in the coupled NOGAPS/TOPS compared with control experiments where SST is prescribed. This implies reduced air/sea temperature differences, consistent with an SST cooling bias.
3. The meridional Hadley circulation in NOGAPS is slightly weakened, suggesting reduced tropical convection. This is consistent with cooler tropical SSTs.

As an example of the coupled systems performance, a NOGAPS/TOPS 10-day SST forecast change (Fig. 4A) and the actual observed change (Fig. 4B) are presented. The plotted area, extracted from the global forecast domain, is the western Pacific during late January, 1991. The model captures the overall cooling outside the tropics and also the warming south of the equator, although details are poorly predicted and the cooling is predicted to be greater than observed, consistent with the global bias. In the area of the Kuroshio current south of Japan, the observed change shows some warming and cooling areas, totally absent in the prediction, which are due to meanders in the Kuroshio. NOGAPS/TOPS was run without a geostrophic current component for this case and so cannot capture this effect. Only a coupled OGCM can provide the current variability.

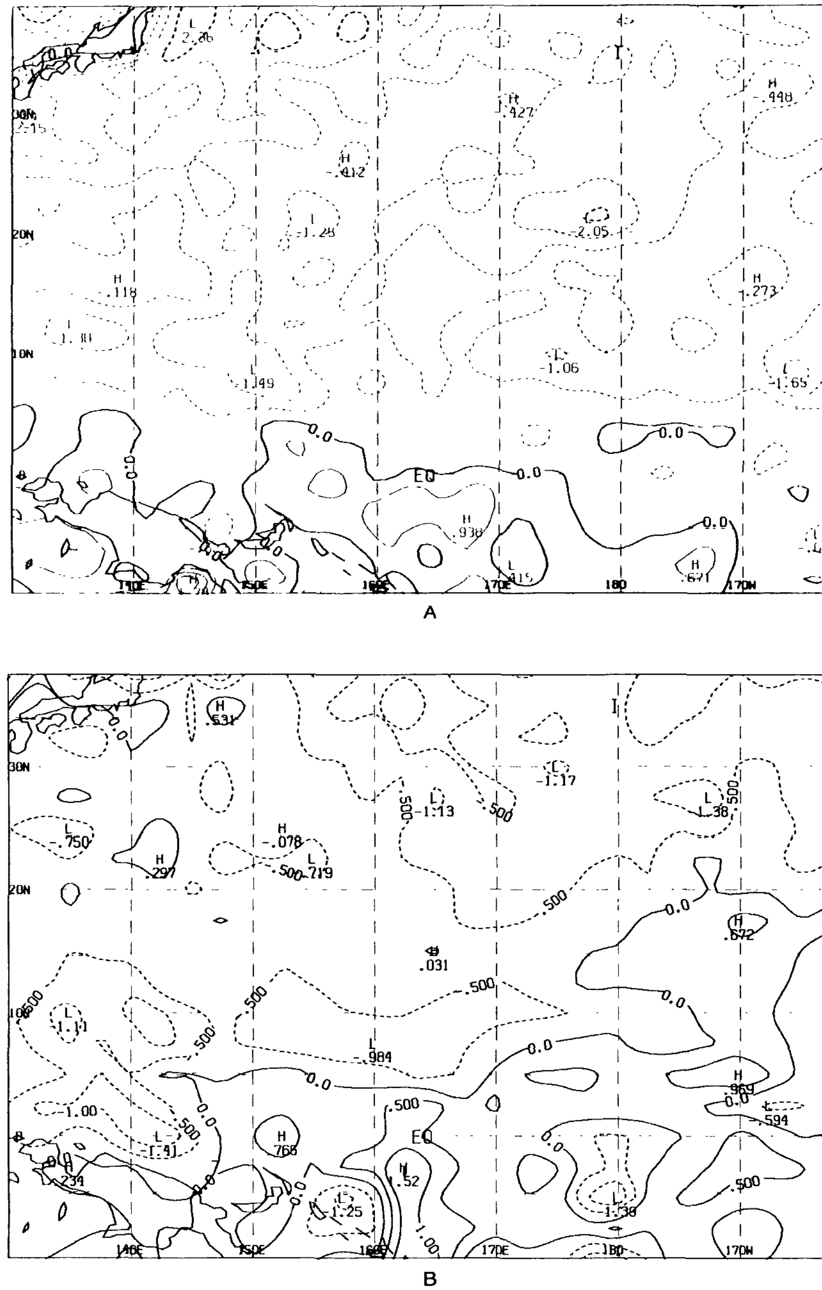

*Fig. 4: (**A**) Ten-day NOGAPS/TOPS predicted change of sea-surface temperature in the western Pacific (valid 1200 GMT, 27 January 1991). Units are °C. (**B**) Ten-day observed change of sea-surface temperature in the western Pacific for same period as in **A** (valid 1200 GMT, 27 January 1991). Units are °C.*

Summary

A pessimistic interpretation of the results shown in the previous section is tempting, but premature. The coupled NOGAPS/TOPS has shown itself to be an extremely sensitive indicator of systematic errors and therefore an excellent research tool for the reduction of these biases. Coupled model results have contributed to several NOGAPS changes that reduced the systematic error. Although most of the research and testing for these improvements did not use the coupled NOGAPS/TOPS directly, the impact of the changes on the coupled system is an important test. Reduction in systematic error improves all applications dependent on NOGAPS, and the operational TOPS/OTIS particularly benefits from better surface fluxes. Therefore, though the fully coupled NOGAPS/TOPS is not yet a competitive alternative to the present loosely coupled systems, it is already an important contributor to overall progress in coupled model development. Navy operations are benefiting from improvements in NOGAPS and TOPS. The goal of an operational fully coupled NOGAPS/TOPS is the ultimate prize of current research efforts, but the benefits derived along the way are also important.

Acknowledgements

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