Navy Operational Global Atmospheric Prediction System (NOGAPS):

Forcing for Ocean Models

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Modeling the interactions between the atmosphere and ocean has become a very active research area in the meteorological and oceanographic communities in recent years. Several factors have contributed to this trend. Most prominently, perhaps, is the great public interest in climate change, i.e. global warming, and the role that atmosphere-ocean interactions have on the Earth's climate. But atmosphere-ocean interactions are not just important on climate change time scales. During 1997 and 1998 a major El-Niño event demonstrated how dramatically changes to global air-sea interactions patterns affect even short-term weather behavior around the world. The societal and economic impacts of both climate change and anomalous weather during El-Niño events are enormous, so clearly improving our ability to accurately model atmosphere-ocean interaction must be a top priority for the meteorological and oceanographic communities.

In this paper we discuss the Navy Operational Global Atmospheric Prediction System (NOGAPS) in its role as the primary source of forcing for U.S. Navy ocean models and modeling atmosphere-ocean interactions. Our emphasis is on relatively short time scales of numerical weather prediction (NWP), since the climate problem is not a Navy priority. Several design decisions for Navy coupled systems are influenced by this emphasis, as discussed by Rosmond (1992). For the climate problem it is necessary to model atmosphere-ocean interactions in a tightly coupled two-way mode, so the atmospheric model and ocean model become essentially one model. This is clearly the most natural way to approach the coupling problem, but some difficult issues still plague many coupled climate models, most notably the climate drift problem (Bryan, 1998) and the need for flux correction (Meehl, 1995). For the shorter time scales of interest here, a one-way coupling strategy (Rosmond, 1992) is used. The essential difference between the two strategies is the time interval of information exchange between the atmosphere and ocean models; for two-way interaction it is typically on the order of a model time step (e.g. 20 minutes), while for one-way interaction it is usually several hours. NOGAPS typically produces surface flux (heat and momentum) forcing for Navy ocean models every three hours during a 6–7 day forecast. We refer to this as one-way interaction because the sea surface temperature (SST) and sea ice coverage, the only ocean model variables NOGAPS 'feels', are held fixed during the forecast. However, there is feedback from the ocean to NOGAPS at the beginning of each of these forecasts. Every 12 hours new global SST and sea ice fields are produced from the Navy's operational ocean modeling system, largely from satellite based observations. So every NOGAPS forecast starts with a bottom boundary condition from the most current ocean surface information available. Because this boundary condition is based on actual observations, and it is not allowed to vary during the forecasts, climate drift is unlikely to occur unless the ocean surface is unobserved for many weeks, for example in areas of persistent near surface stratus clouds. Currently the operational SST and sea ice analyses assume persistence as the background, so in the absence of observations these fields remain fixed and cannot capture naturally occurring changes at the ocean surface such as seasonal overturning. Allowing the SST and sea ice to change between analysis times due to NOGAPS surface flux forcing can possibly predict these important changes, but only if the fluxes are able to maintain reasonable conditions at the air-ocean interface, i.e. no significant departure from climatology.

Currently NOGAPS forcing drives the following operational or real-time testing ocean models at the

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Fleet Numerical Meteorology and Oceanography Center (FNMOC) and at the Naval Oceanographic Office (NAVO):

- Ocean wind wave model (WAVEWATCH)
- Thermodynamic Ocean Prediction System (TOPS)
- Polar Ice Prediction System (PIPS)
- Princeton Ocean Model (POM)
- NRL Layered Ocean Model (NLOM)
- Navy Coastal Ocean Model (NCOM)
- Advanced Circulation Model (ADCIRC)
- Shallow Water Assimilation Forecast System (SWAFS)
- Ocean wind wave model (WAM) (a predecessor to WAVEWATCH)

Surface fluxes of momentum (drag), latent and sensible heat flux, precipitation, solar and long wave radiation, surface air temperature and surface pressure are standard NOGAPS output products used as input to these systems. Because NOGAPS and the ocean models listed above normally do not run on the same computational grids, a software interface called a flux-coupler is used to ensure consistent and accurate interpolations that conserve important physical quantities such as mass, energy, and momentum.

The NOGAPS fluxes that drive Navy ocean models are defined only at the surface or within the planetary boundary layer (PBL). However, their quality depends on much more than the formulation of the NOGAPS PBL. Interactions with the other parameterizations of solar and long-wave radiation, cumulus convection, and especially clouds are extremely important. Hack (1998) found that changes to the cumulus convection parameterization in the NCAR (National Center for Atmospheric Research) community climate model (CCM3) had more impact on improving meridional heat transport than any other physical process. NOGAPS model performance has historically been rather insensitive to changes in the surface flux and PBL parameterizations, with essentially the same scheme running for nearly 20 years of operational use. During this same period NOGAPS has seen dramatic improvements due to changes in other parts of the forecast system, including other physical parameterizations. Only recently, however, has the impact of NOGAPS changes on surface fluxes that force ocean models been included in our overall evaluation of NOGAPS performance.

In this paper we will examine some of the recent changes to NOGAPS that have had significant impact on forecast performance, specifically with regard to the surface flux products used to force Navy ocean models. We provide a brief description of the operational NOGAPS, followed by a description of NOGAPS operational processing. Two recent improvements to the NOGAP forecast model are then described: a new low-level cloud parameterization and a new cumulus parameterization. Both have a beneficial impact on NOGAPS surface fluxes and overall model performance. We compare the improved NOGAPS surface fluxes of heat and moisture to independent validation data. We then show two recent results from Navy operational ocean models driven by NOGAPS fluxes. Finally we summarize the overall impact of recent model changes on NOGAPS forcing for Navy ocean models and give an outlook for the future.

NOGAPS model description

The NOGAPS forecast model is a spectral general circulation model (GCM), with many features common to other climate and NWP models run at major research and operational facilities around the world. The model has been under continuous development at the Naval Research Laboratory (NRL), Monterey, California, for over 20 years. Operationally the model is run by FNMOC in support of worldwide Department of Defense (DOD) activities. Nearly every atmospheric and oceanographic application of interest to DOD is in some way dependent on NOGAPS products.

Hogan and Rosmond (1991) and Rosmond (1992) describe NOGAPS details, so only a quick overview is necessary here, emphasizing the changes introduced over the past 10 years. A significant increase to the operational model horizontal resolution, from T79 (~160 km) to T159 (~80 km) has occurred because of upgrades to the FNMOC operational computer system. This yields better predictions of precipitation, frontal system structure, tropical cyclones, and other mesoscale features, which in turn have improved the quality of the surface fluxes coming from NOGAPS at these scales. The physical parameterizations for solar and long wave radiation, clouds, and cumulus convection have been changed significantly; in the case of the cumulus scheme completely replacing the Arakawa-Schubert scheme with the Emanuel scheme. The following sections discuss the impact of these changes.

NOGAPS operational processing

NOGAPS is a complete atmospheric forecast and data assimilation system, starting with raw meteorological data from all over the world and from a myriad of observing systems, and ending with a vast set of gridded meteorological "products". The processing consists of the following automated steps, done every 6 hrs at 00UTC, 06UTC, 12UTC, and 18UTC, and often described as an "update cycle":

(1) Objective quality control of the raw input data to eliminate duplicate and likely erroneous observations;

(2) Multivariate optimum interpolation (OI) objective analysis: combining the observations and NOGAPS model generated background fields, i.e. the "first guess", to produce a set of initial fields at the current analysis time;

(3) Forecast from the analyzed initial conditions: At 00UTC and 12UTC the forecast length is 144 hours, at 06UTC and 18UTC only 18 hour forecasts are

made to provide background forecasts for the subsequent analyses;

(4) Post-processing to produce output products: currently about 25000 global 1-degree fields at standard vertical levels from sea level to the top of the atmosphere. These are interpolated from the NOGAPS computational grid;

(5) Diagnostics and verification statistics, including comparison with other operational centers.

Ocean models often benefit from relatively high frequency atmospheric forcing, in particular in the mixed layer where inertial oscillations are excited by transient forcing from surface winds. The NOGAPS fluxes are output at 3-hour intervals to support this requirement. In the future this frequency may be increased to every hour, and also at higher horizontal resolution, for example 0.5 degrees, to take full advantage of anticipated increases in NOGAPS resolution. Other model improvements should also benefit Navy ocean models; two recent examples are described below.

NOGAPS low level cloud parameterization

Boundary layer clouds have a major impact on the global ocean. Stratocumulus reflects a substantial amount of solar radiation and consequently has a large cooling effect on the ocean surface. Subtropical boundary layer clouds, in general, have a major role in determining the tropical and subtropical atmospheric circulation (e.g. Philander et al., 1996; Siebesma, 1998). Arctic stratus controls the thermodynamic balance of the polar boundary layer with the subsequent impact on the sea ice thickness and distribution.

A realistic representation of boundary layer clouds in global atmospheric models has been a major issue in weather and climate prediction for a long time (e.g. Randall et al., 1985). In spite of some progress in this area, subtropical boundary layer clouds are often not realistically represented in global models, and stratocumulus, in particular, is often severely underestimated (e.g. Duynkerke and Teixeira, 2001). Consequently the solar radiation flux into the ocean surface is overestimated in these areas, and in coupled ocean-atmosphere models, this leads to large positive SST biases (Li and Hogan, 1999).

In this section a new NOGAPS prediction scheme for cumulus and stratocumulus clouds is discussed. The new cloud parameterization is a combination of two simple schemes: (1) a diagnostic cloud fraction scheme for cumulus, based on a steady state version of the prognostic cloud fraction equation suggested by Tiedtke (1993) and (2) a simplified version of the statistical cloud scheme suggested by large eddy simulation (LES) studies from Cuijpers and Bechtold (1995).

The NOGAPS forecast model with a resolution of T63L24 (~1.9 degrees horizontal resolution, 24 levels) was used to simulate the June-July-August (JJA) season of 1999. The simulation was run with the FNMOC

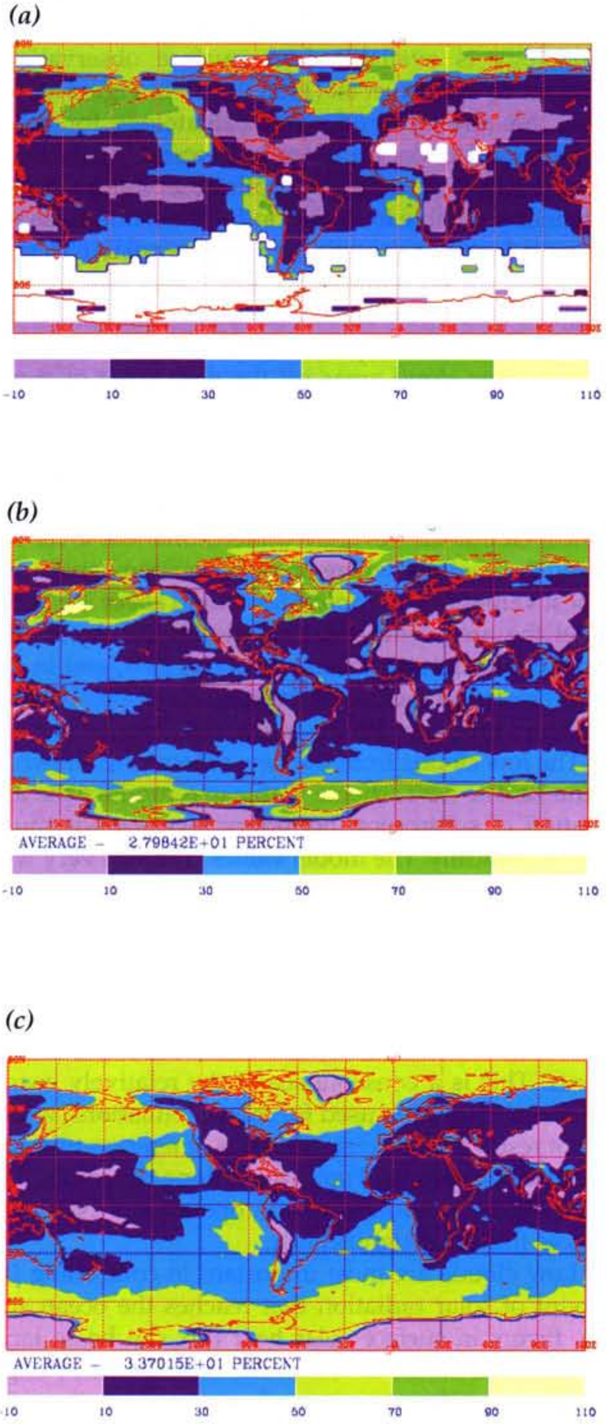


Figure 1. ***a)*** *Low stratus cloud cover global distribution, according to the climatology of Warren et al. (1986, 1988) for the June-July-August (JJA) 1999 season. The cloud cover units are in percent (%). White areas indicate inadequate data for meaningful climatology.* ***b)*** *Low clouds from the NOGAPS control model for JJA 1999. The cloud cover units are in percent (%).* ***c)*** *Low clouds from NOGAPS with the new cloud scheme for JJA 1999. The cloud cover units are in percent (%).*

operationally produced SST analyses updated every day during the period to provide realistic bottom boundary conditions over the oceans. A stratus cloud climatology is available from surface observations compiled by Warren et al. (1986, 1988). In Figure 1a the global low stratus cloud cover climatology for JJA is shown (cloud cover units are in percent). This climatology is based on surface synoptic observations, and is particularly reliable for low clouds. The white areas are regions where not enough data were available to produce a statistically significant climatology. The areas of the globe where low clouds are most frequent during the Northern Hemisphere (NH) summer are the marine status cloud areas off the west coast of continents and the Arctic, and the fog regions off the northeast coasts of continents.

In Figure 1b the NOGAPS low clouds for the control simulation are shown. It can be seen that the subtropical clouds are severely underestimated. Over the ocean, the regions where the observations show the highest values of subtropical low cloud cover are in the model the areas with least clouds. In the Arctic, the model overestimates stratus by about 20%, and in the deep convection regions of the western tropical oceans the model produces far too much low cloudiness.

The low clouds from the new scheme are shown in Figure 1c. The new scheme is able to reproduce the distribution of subtropical boundary layer clouds much more realistically. The model values compare very well with the observations, with cloud cover above 50% in large areas of the subtropics. The new scheme also produces more realistic cloud cover in the Arctic and in the western tropical oceans. One noticeable deficiency with the new scheme is the displacement of the subtropical cloudy areas away from the west coasts of continents. This is a consequence of the relatively coarse horizontal resolution used for these simulations, which cannot resolve the strong gradients of temperature and moisture between land and water along the coasts. The much higher resolution of the operational NOGAPS reduces this error significantly.

Low clouds are most important in controlling the amount of solar radiation that reaches the ocean surface. Errors in surface solar heat flux can be so large that all other terms in the ocean surface heat budget become insignificant, so it is informative to see how the improvements in NOGAPS cloud prediction described above affect the solar energy budget in NOGAPS. In Figure 2a the ocean climatology of net surface shortwave radiation (SSWR), for the JJA season is shown (the units are in Wm^{-2}). This climatology is based on COADS data (Da Silva et al., 1994). The white areas are either land or regions where the values are less than 20 Wm^{-2}. The eastern regions of the subtropical oceans have lower values of SSWR than the western counterparts. This is due to boundary layer clouds in the eastern areas of the subtropical oceans. In Figure 2b, the NOGAPS SSWR for the JJA 1999 control simulation is

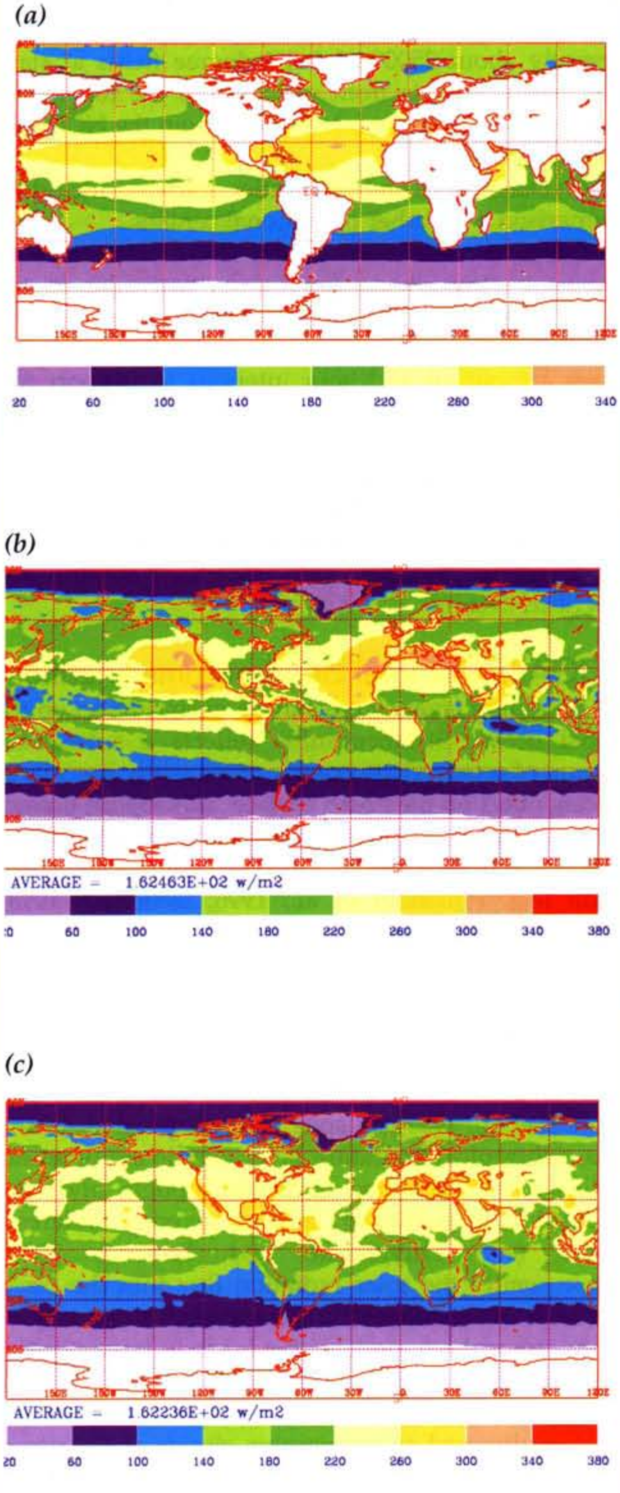


Figure 2. ***a)*** *Ocean climatology of net Surface Short-Wave Radiation (SSWR), for the JJA 1999 season based on Da Silva (1994). The units are in W/m^2.* ***b)*** *SSWR from the NOGAPS control model for JJA 1999. The units are in W/m^2.* ***c)*** *SSWR from NOGAPS with the new cloud scheme for JJA 1999. The units are in W/m^2.*

shown. In the control model, the SSWR in the stratocumulus and cumulus regions is severely overestimated; up to nearly 100 *Wm*$^{-2}$. In the climatology, the eastern side has lower values of SSWR due to subtropical clouds, in the control model; however, the SSWR is much lower in the western side of the ocean. Such a major difference between the model and the climatology clearly would have serious consequences in terms of coupled ocean-atmosphere modeling.

The SSWR results with the new scheme are shown in Figure 2c. The subtropical SSWR is reproduced in a more realistic way with the new scheme. There is a better agreement between the observations and the new model in the major stratocumulus and cumulus regions off western North and South America and Namibia. The simulation of "cold tongues" of low SSWR in the equatorial east Pacific and Atlantic are also quite well reproduced.

Emanuel Cumulus Parameterization

Cumulus convection parameterization is one of the most important mechanisms in global forecast models for maintaining realistic meridional heat transport between the tropics and higher latitudes. This has been the experience with NOGAPS and also with similar global forecast or climate models such as CCM3 (Hack, 1998). One of the most significant recent improvements made to the NOGAPS forecast model is the introduction of the Emanuel scheme (Emanuel, 1991; Emanuel and Zivkovic-Rothman, 1999) for convective parameterization. The Emanuel scheme has a prognostic equation for cloud base mass-flux and an episodic entraining mass-flux cloud model. These characteristics of the scheme make it unique from most other entraining-plume convective parameterization schemes. The Emanuel scheme reduces NOGAPS systematic errors compared to the errors with the relaxed Arakawa-Schubert scheme (Arakawa and Schubert 1974; Moorthi and Suarez, 1992) originally used in NOGAPS. For example, near surface winds are particularly important for ocean model forcing in the tropics. Introduction of the Emanuel scheme into NOGAPS improves tropical wind predictions significantly compared to the model performance with the original Arakawa-Schubert scheme (Figure 3).

Despite the overall encouraging performance of the Emanuel scheme, the scheme as originally formulated does show some weaknesses. For example, forecasts using the Emanuel scheme produce insufficient rain in heavy-precipitation events and have an overall weak wind bias. In addition, the mean vertical heating profile in the tropics shows a large warming near 200 hPa that does not conform well to the observations. However, the scheme is fairly new in the atmospheric science community, with great potential for improvement. We (NRL Monterey) are aggressively working to improve the scheme. We find that making the vertical entraining cloud mass-flux profile dependent on the buoyancy, instead of the vertical buoyancy gradient as in the original design, leads to an overall reduction in systematic errors, including the upper level warm bias and weak wind bias.

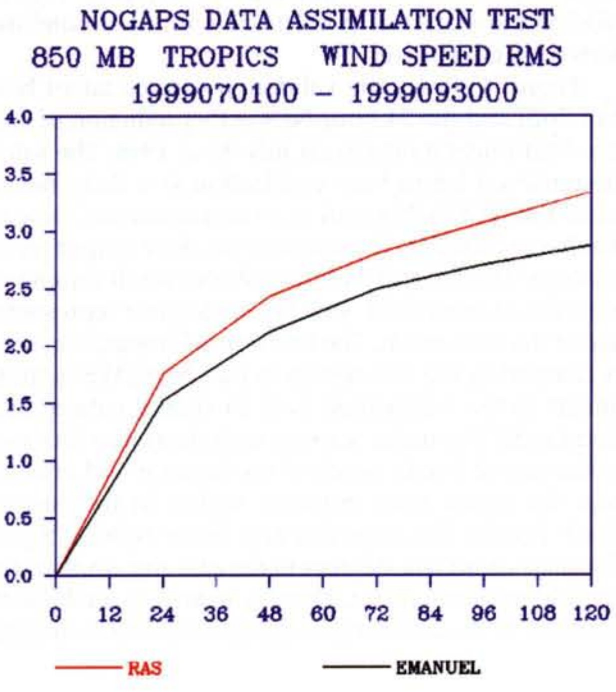


Figure 3. RMS tropical wind speed errors (m/sec) comparison (July–August, 1999) for NOGAPS model with Arakawa-Schubert convection (RAS) vs. Emanuel convection. X-axis is forecast time in hours.

Validation of Surface Fluxes

Due to sparse *in situ* measurements of meteorological parameters, estimation of ocean surface fluxes as well as other surface parameters for the validation of model prediction has always been a challenge. Recently, a collaborative effort between the University of California at Santa Barbara (UCSB) and the Jet Propulsion Laboratory (JPL) has produced a near operational estimation of surface fluxes over tropical Pacific ocean (Jones et al., 2001). In their approach, the surface air temperature and specific humidity are estimated from the special sensor microwave/imager (SSM/I) satellite data and the National Centers for Environmental Prediction (NCEP/NCAR) reanalysis through training of artificial neural networks. This data along with the SSM/I retrieved surface wind speed are used to estimate the daily average of the surface sensible and latent heat fluxes over tropical Pacific Ocean between 110°E and 70°W and 30°S to 30°N. This data set, with its high spatial resolution of 0.25 degrees in latitude/longitude, is a relatively independent data source for validating numerical model predictions over broad regions. In the following, we compare T79L24 NOGAPS surface flux predictions with these satellite-derived surface fluxes.

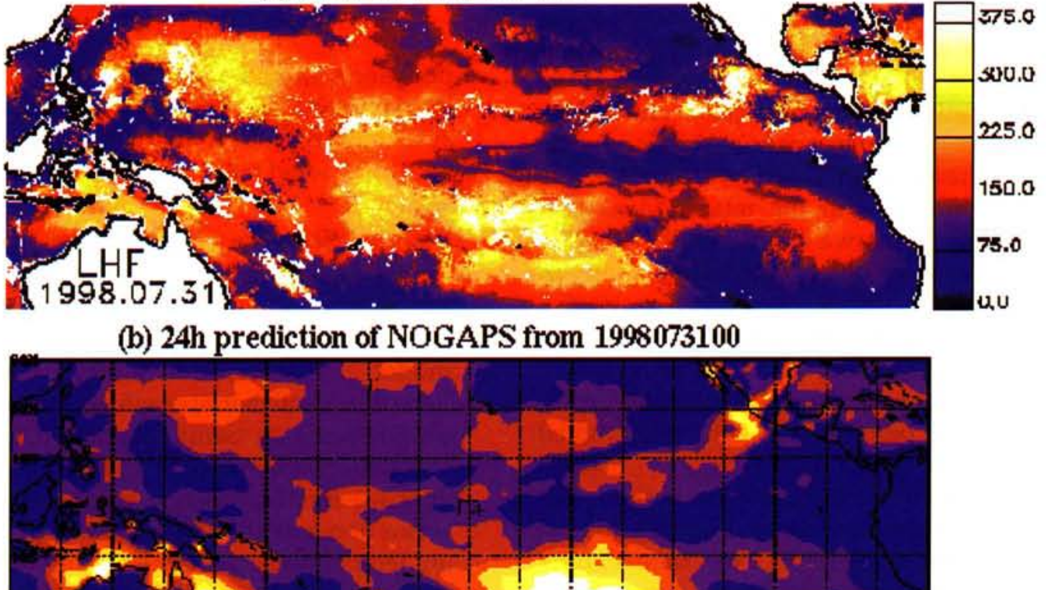
Figure 4 shows the validation surface latent heat flux (top) and the 24-hour NOGAPS prediction of surface latent heat (bottom) on July 31 of 1998. The satellite-retrieved latent heat verification is a daily mean, while the NOGAPS result is an instantaneous view of the flux at 24 hours. Examination at other output times between 0 hours and 24 hours shows small difference from the 24-hour field, so it is an adequate representative of the time mean. The first overall impression seen in comparing the two results is that NOGAPS is quite similar to the verification both in spatial pattern and magnitude. The major features include a large flux area in the central Pacific south of the Equator and another near the storm track entrance region in the eastern North Pacific. The large flux area in the NOGAPS prediction is about five degrees to the east and south of the satellite-retrieved result. There is an area of small latent heat flux in the cold tongue region from the west coast of South America extending to the central Pacific along the Equator. Small fluxes also occur at the storm track exit region near the west coast of North America. Of particular interest is a small comma-shaped area with very large latent heat flux near 109°W and 18°N in both the NOGAPS forecast and the verification. This feature is associated with Hurricane Estelle, which occurred at this time. The similarity is particularly encouraging given the rather coarse NOGAPS resolution (approximately 150 km). The maximum value in the NOGAPS prediction is slightly above 450 Wm^{-2}, while the satellite-retrieved maximum is above 375 Wm^{-2}. The satellite-derived latent heat flux has a root-mean-square error of approximately 47 Wm^{-2}, so the difference between the model prediction and verification is nearly within the error range of the validating data.

The sensible heat fluxes for the same time are shown in Figure 5. The overall pattern is similar to the latent heat flux. But the comparison between the model prediction and the validation shows larger discrepancies than for the latent heat fluxes. In NOGAPS the position of the maximum in the southern Pacific is

Latent Heat Flux on Tropical Pacific Ocean

(30N-30S,110E-70W)

(a) Satellite-derived LHF



(b) 24h prediction of NOGAPS from 1998073100

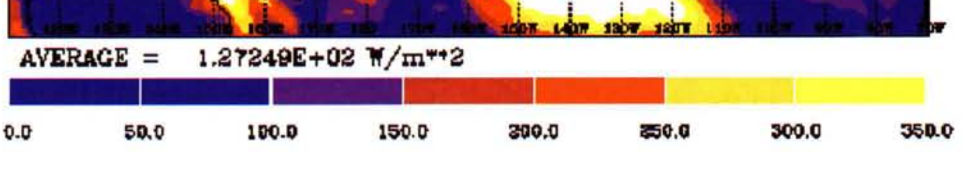
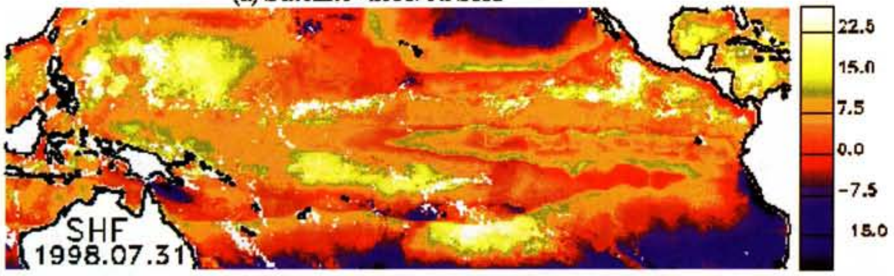


*Figure 4. Tropical Pacific observed **a)** latent heat flux for 31 July 1998, and **b)** NOGAPS predicted latent heat flux for 31 July, 1998. Units are W/m².*

Sensible Heat Flux on Tropical Pacific Ocean

(30N-30S,110E-70W)

(a) Satellite-derived SHF



(b) 24h prediction of NOGAPS from 1998073100

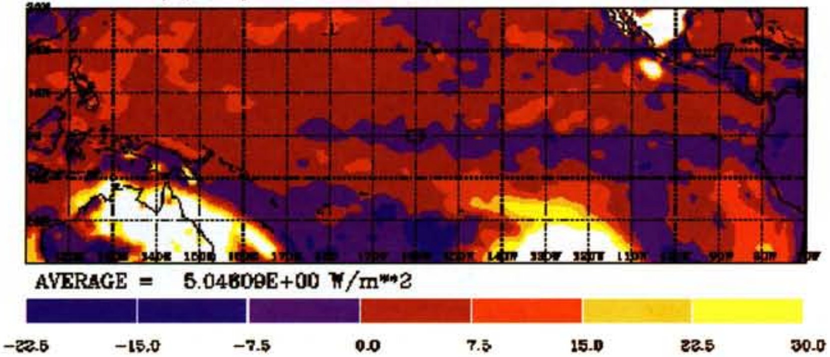
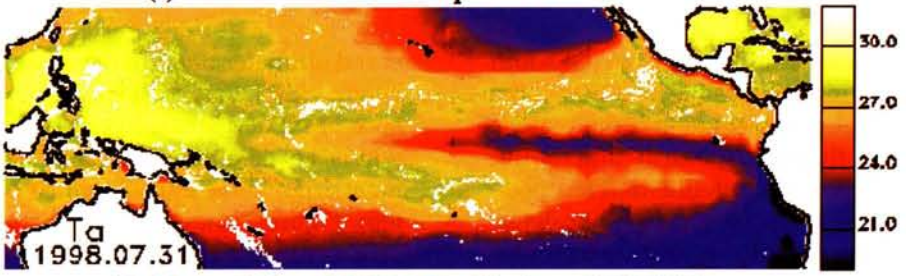


Figure 5. *Tropical Pacific observed* ***a)*** *sensible heat flux for 31 July 1998, and* ***b)*** *NOGAPS predicted sensible heat flux for 31 July 1998. Units are W/m².*

Air Temperature at 3m/2m height on Tropical Pacific Ocean

(30N-30S,110E-70W)

(a) Satellite-derived air temperature at 3m



(b) 24h prediction of NOGAPS at 2m from 1998073100

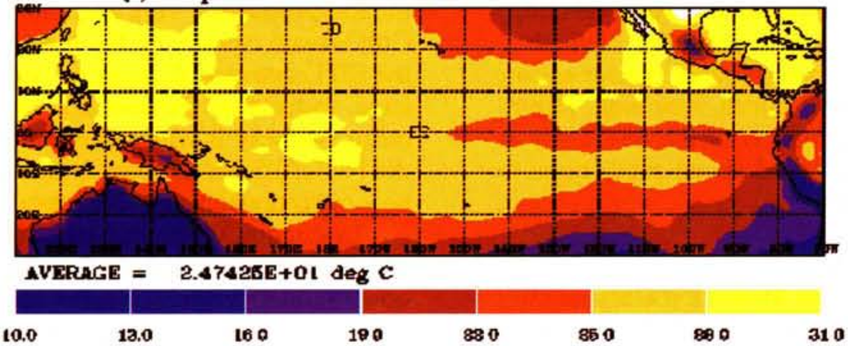


Figure 6. *Tropical Pacific observed* ***a)*** *surface air temperature (3 m) for 31 July 1998, and* ***b)*** *NOGAPS predicted surface air temperature (2 m) for 31 July 1998. Units are deg C.*

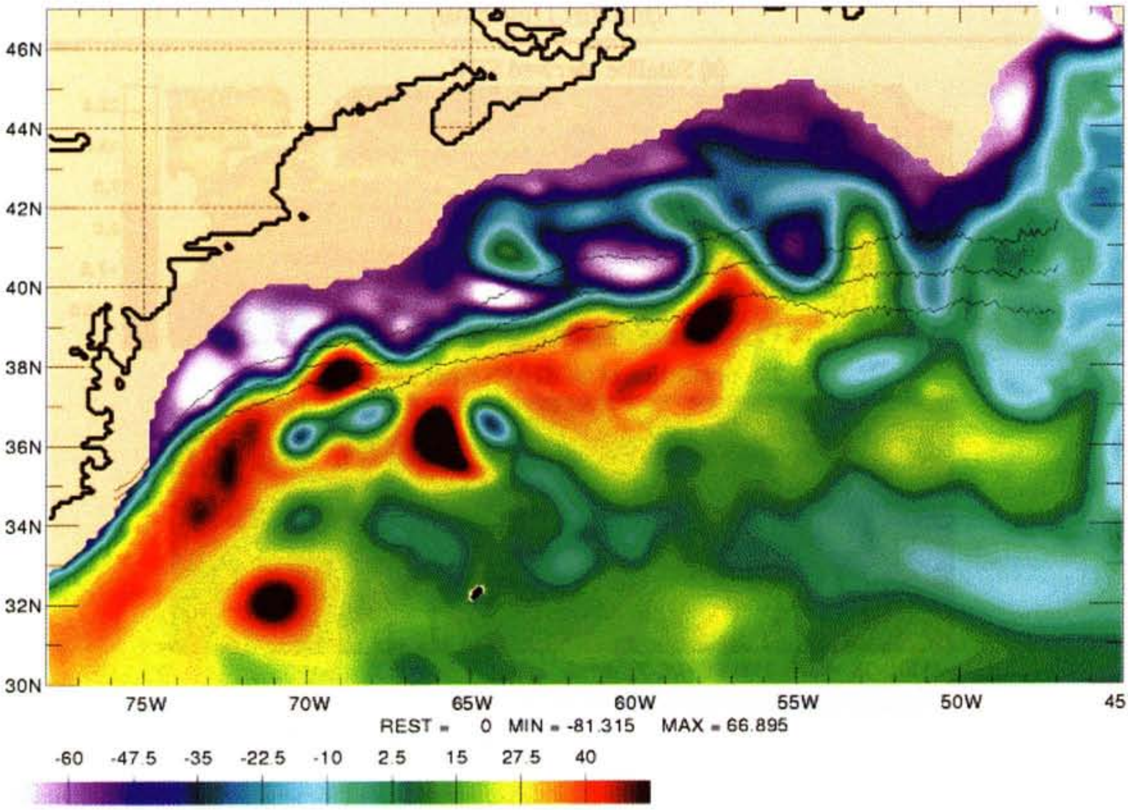


Figure 7. Gulf Stream as simulated by NLOM forced by NOGAPS surface winds. The three thin lines show the observed mean position of the north wall and +/- 3 standard deviations about this mean calculated from satellite IR data. Units are height in cm.

about 10 degrees to the east and 5 degrees to the south of the verifying maximum. The sensible heat flux in the storm track entrance region is weaker and the regions with downward heat fluxes off North and South America are displaced from the satellite-derived positions. Since the sensible heat fluxes are mainly determined by the air-sea temperature difference and surface wind speed, in Figure 6 we compare the 3 m air temperature deduced from the satellite-retrievals (top) and the 2 m model prediction (bottom). Note that, while the sensible heat fluxes showed discrepancies, the surface air temperatures match very well. Future study will focus on examination of the SST analysis and the NOGAPS surface wind speed predictions to explain these discrepancies.

Ocean Model Results

The NRL Layered Ocean Model (NLOM) recently underwent an operational test as part of its implementation at the Naval Oceanographic Office (Rhodes et al., 2002). The model runs at $\frac{1}{16}$° horizontal resolution as part of a global data assimilation system of satellite based altimeter data that analyzes dynamic sea surface height (SSH). Part of the testing evaluated the performance of NLOM when forced only by NOGAPS surface winds, i.e. no altimeter data ingested, to assess the "climate drift" in the unconstrained NLOM/NOGAPS system. Figure 7 shows a snapshot of the simulated SSH on a day in late winter 2001. The combination of NLOM very high horizontal resolution and NOGAPS wind forcing produces a very accurate mean position of the Gulf Stream, shown by the three thin lines overlaying the SSH contours. Because no ocean data were assimilated, individual features do not verify well, but the mean pathway is well represented. From these results the NOGAPS winds seem quite adequate to drive this new operational Navy ocean model.

Evaluation of the impact of NOGAPS parameterization changes on the surface fluxes that force Navy ocean models is a challenging problem because of the long time scales of ocean response to this forcing. Integration over several years is typically required to get statistically meaningful results comparing a control and NOGAPS change experiment. The computational

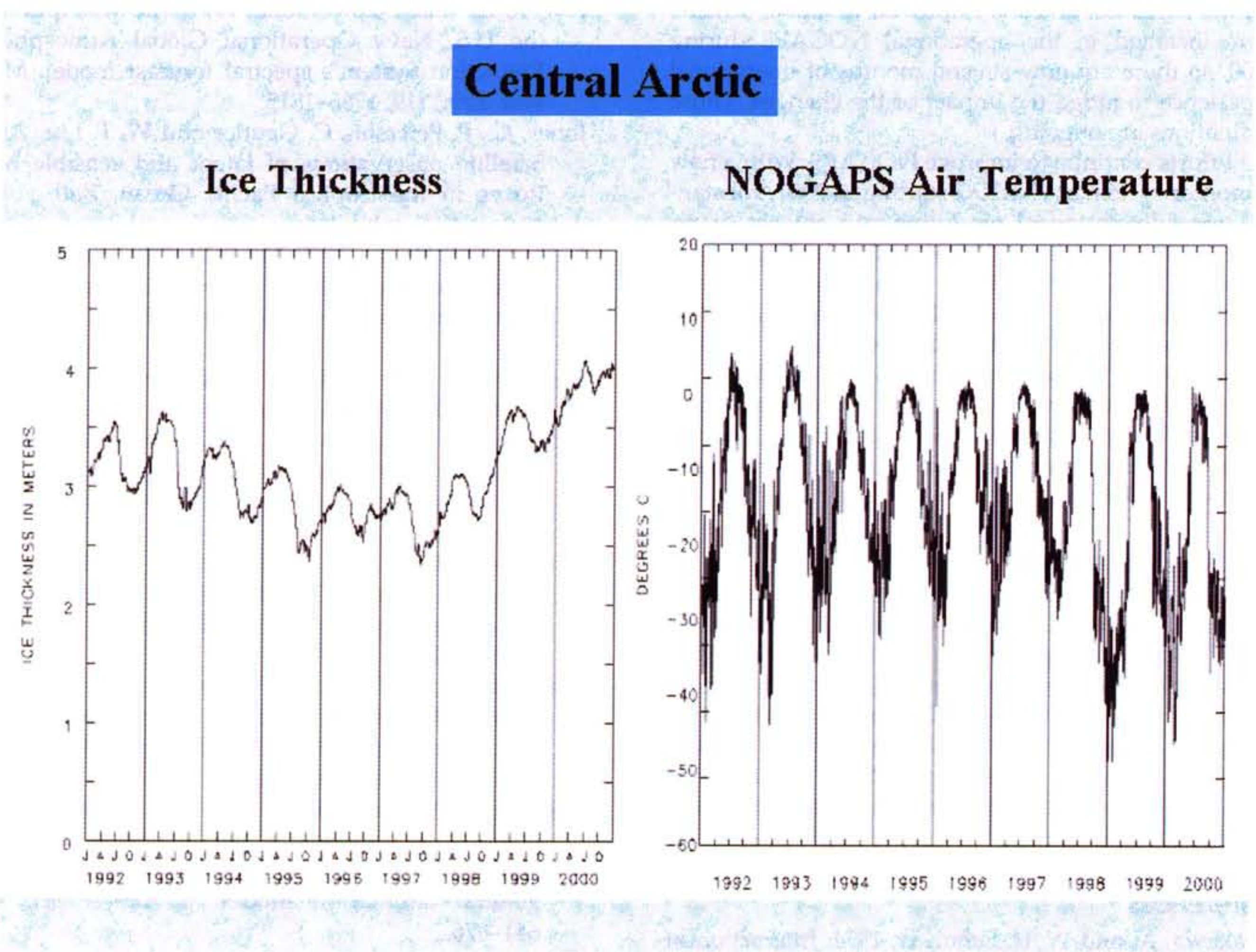


*Figure 8. Nine years of operational PIPS model Arctic ice thickness **(left)** vs. NOGAPS surface air temperatures **(right)**. Note the abrupt change between 1997 and 1998, coinciding with a change in the NOGAPS long wave cloud water/ice parameterization.*

resources available are simply inadequate to perform such experiments. The only alternative is to monitor the ocean models being forced to assess possible adverse effects due to NOGAPS changes, and use this as guidance for subsequent changes. The only Navy ocean model with a sufficiently long, unbroken history of response to NOGAPS forcing to make such assessments is the operational ice model PIPS (Preller et al., this issue) running over the Arctic Ocean. Figure 8 is from Preller et al. (2001) showing a nine-year time series comparing central Arctic sea ice thickness and NOGAPS surface air temperatures. During 1997 a change to the representation of cloud water/ice in the long wave radiation parameterization lead to a significant cooling of wintertime surface air temperatures. Ice thickness predicted by PIPS is a function of the internal dynamics of the model and the heat balance between the atmosphere, ice, and underlying ocean; no ice thickness observations are used. Clearly the NOGAPS change caused an ice thickening trend, replacing a thinning trend prior to 1997. A warm temperature bias was probably replaced with a cold bias. The changes to the NOGAPS low cloud parameterization described in a previous section are partially motivated by an effort to correct this apparent bias and stabilize the PIPS ice thickness predictions. It will probably take at least two more winters of PIPS performance data to assess our success toward this goal.

Summary

In this short review we present results from recent efforts to improve NOGAPS surface fluxes used to force operational Navy ocean models. Clearly the results shown are quite preliminary; assessing the performance of the ocean models driven by the NOGAPS products will be the true validation. Both the new cloud parameterization and the improved Emanuel scheme were installed in the operational NOGAPS during 2000, so there are now several months of operational experience to judge the impact of the changes. Those evaluations are ongoing.

Efforts continue to improve NOGAPS. With a new computer system at FNMOC starting in 2001, substantial upgrades to model resolution and physical parameterizations are planned. Also under development is a coupled NOGAPS/global ocean model system, which will allow us to come closer to the 2-way interaction design. New satellite data sources to observe eddy-resolving ocean circulation features will be incorporated into this new system. The ultimate goal is a truly unified earth system model coupling all components of the Earth's environment, but that is still many years away.

Acknowledgements

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