3.10 ON THE IMPACT OF IMPROVED DYNAMICS AND PHYSICS IN THE GEOS-2 GCM

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1. INTRODUCTION

The Goddard Earth Observing System (GEOS) General Circulation Model (GCM) has been developed by the Data Assimilation Office (DAO) at the Goddard Laboratory for Atmospheres (in collaboration with the Climate and Radiation Branch) for use in the system to analyze EOS data. An early version of this system (GEOS-1, Takacs et al. (1994)) was used to produce a multi-year global atmospheric data set for climate research (Schubert et al., 1993). In addition, this model produced multiple 10-year climate simulations as part of the DAO's participation in the Atmospheric Model Intercomparison Project (AMIP-1) sponsored by the Program for Climate Model Diagnostics and Intercomparison (PCMDI) (Gates, 1992). Based on extensive analysis and evaluation of the GEOS-1 system (see Takacs and Suarez (1996), Molod et al. (1996), Schubert et al. (1995), Schubert and Rood (1995)), the GEOS-2 GCM was developed to address some of the fundamental limitations of GEOS-1. The GEOS-2 GCM is targetted to support the Terra platform of the EOS project, and will provide the benchmark for future model development within the DAO.

2. MODEL DESCRIPTION

The GEOS-2 GCM is constructed in the horizontal using the staggered Arakawa C-grid and employs Version 2 of the Aries/GEOS Dynamical Core for the finite-differencing algorithm. Important differences relative to GEOS-1 include:

- 4th-order horizontal differences instead of 2nd-order
- raising the model top from 10 hPa to 0.01 hPa
- increasing the horizontal and vertical resolution from 2°x2.5° x 20 Levels to:
  - 2°x2.5° x 70 Levels
  - 1°x1° x 48 Levels

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Version 2 of the Aries/GEOS Dynamical Core is a fourth-order version of the Sadourny energy and potential enstrophy conserving scheme described by Burridge and Haseler (1977), and has been generalized to allow for a non-uniform latitude/longitude ($\Delta\phi_j$, $\Delta\lambda_i$) spherical grid (see Suarez and Takacs (1995)). This scheme conserves total energy and potential enstrophy for the non-divergent component of the flow. It is fourth-order in the sense that it reduces to the fourth-order Arakawa (1966) Jacobian for non-divergent flow, thereby providing fourth-order accuracy for the advection of a second-order vorticity. Horizontal advection of potential temperature, moisture, and passive tracers is performed using a first- and second-moment conserving fourth-order scheme developed at UCLA (Arakawa, personal communication). It also is fourth-order only in the advection by the non-divergent part of the flow. The use of fourth order differencing substantially improves the phase propagation of synoptic scale waves. In the vertical, the Aries/GEOS Dynamical Core uses a Lorenz or unstaggered grid in generalized sigma coordinates following Arakawa and Suarez (1983).

The raising of the model lid is directed at improving stratospheric descent over the winter pole and addressing the stratospheric cold pole problem. Increasing the number of levels is directed at improving the representation of the planetary boundary layer, the troposphere at the altitude of the sub-tropical jet stream, and the stratosphere. Increasing the horizontal resolution improves numeric accuracy and provides for a more realistic representation of storms and fronts.

The GEOS-2 GCM physics package includes a full set of sub-grid parameterizations as well as a coupled land surface model. Penetrative and shallow cumulus convection are parameterized using the Relaxed Arakawa-Schubert scheme of Moorthi and Suarez (1992), coupled with a Kessler-type scheme for the re-evaporation of falling rain (Sud and Molod, 1988). The radiation parameterization in GEOS-2 has been completely updated from GEOS-1 to improve the radiative transfer in the stratosphere and to model photosynthetically active radiation for the land surface model.

In addition the radiative packages allow more accurate cloud radiative computations, and are suitable for both aerosols and minor trace gases. A detailed description of these packages are found in Chou (1990,1992,1998), and Chou and Suarez (1994).

Turbulent eddy fluxes of momentum, heat, and moisture in the surface layer are calculated using stability-dependent bulk formulas based on Monin-Obukhov similarity functions. Above the surface layer, turbulent fluxes of momentum, heat, and moisture are calculated by the Level 2.5 Mellor-Yamada type closure scheme of Helfand and Labraga (1988), which predicts turbulent kinetic energy and determines the eddy transfer coefficients used for a bulk formulation. The scheme has been recently modified to account for buoyancy generated by moist processes by including the effects of small-scale condensation and evaporation. The moist scheme also predicts liquid-water content and fractional cloud cover associated with shallow cumulus and stratocumulus clouds. These cloud properties are allowed to interact with the GCM's radiation parameterizations.

The upper-air turbulence and surface flux package is fully coupled to the Koster-Suarez (1992) Land Surface Model (LSM). The LSM is a Soil-Vegetation-Atmosphere-Transfer (SVAT) model which was based on the Simple Biosphere (SiB) model of Sellers et al. (1986). The predicted quantities are deep soil and canopy temperatures, three soil moisture layers, a canopy interception reservoir, a canopy air specific humidity, and a snow pack. The sub-grid scale variability of the surface is modeled by viewing each GCM grid box as a mosaic of independent vegetation stands, or *tiles*, using linear aggregation/disaggregation formulae for links to the GCM grid. The coupling between the GCM and the tile mosaic involves issues of numerical stability and energy conservation. Fluxes of heat, moisture, and momentum at the land-surface interface calculated by the SVAT must by consistent with those calculated by the GCM surface layer scheme.

Finally, the GEOS-2 GCM employs the gravity wave drag scheme of Zhou et al. (1996) to provide physically based momentum dissipation in the upper troposphere and mesosphere due to orographic forcing.

3. SAMPLE RESULTS AND SUMMARY

Significant improvements have been made to the GEOS GCM since its utilization during the first international reanalysis project. These developments include: 1) improved numerics (2nd-order to 4th-order) with modifications for a variable resolution stretched-grid, 2) the incorporation of the Koster-Suarez land surface model, 3) implementation of moist turbulence within the Level 2.5 turbulence scheme, 4) gravity wave drag, and 5) increased resolution ($2°$x$2.5°$ x 20 levels with ptop = 10 mb, to $1°$x$1°$ x 48 levels with ptop = 0.01mb). These improvements have led to a reduction in model biases of prognostic fields, an improvement of the hydrological cycle and the surface energy balance, and more realistic representations of storms and fronts. These improvements have significant implications for improving the overall quality of the data assimilation system and of the products produced.

We conclude with a few samples of these positive results. Figure 1 compares seasonal December-January-February (DJF) simulations of the sea-level pressure and mean zonal wind from GEOS-1 and GEOS-2 together with the GEOS-1 DAS Re-Analysis. It should be noted that the GEOS-1 DAS sea-level pressure and mean zonal wind were comparable to those of the other re-analysis centers. We see that the errors within the GEOS-1 GCM which caused exececessive zonality , enhanced surface winds and a strong westerly bias at upper levels have been virtually eliminated within the GEOS-2 system. This is primarily due to the inclusion of orographic gravity wave drag, as well as increased vertical resolution and the raised lid.

Figure 2 compares a number of zonal mean diagnostic quantities from a $1°$x$1°$ x 48L seasonal (DJF) run to independent observations (COADS for clouds and surface wind fluxes, GPCP for precipitation, and SRB for radiation). While we see general agreement in all quantities, we do note excessive cloud forcing in the tropics and excessive wind stress at high latitudes.

Finally, Fig. 3 demonstrates the impact of horizontal resolution on the representation of storms and fronts. All three forecasts started from the same $2°$x$2.5°$ initial condition obtained from a GEOS-2 DAS analysis. The higher resolution runs interpolated the initial condition to the finer grid. The $0.5°$x$0.5°$ run employed the stretched-grid feature of the GEOS GCM which allows a re-distribution of grid points to obtain very high resolution over a selected area of interest. In this case, the $1°$x$1°$ grid was "stretched" to $0.5°$x$0.5°$ between latitudes 25°N and 45°N and longitudes 70°W and 50°W. Outside this region, the grid gradually increases to a maximum on the opposite side of the earth and at the farthest pole. The figure shows results just beyond a two day forecast (53 hours). We see that as resolution increases, the intensity of the developing low pressure system in the Atlantic is enhanced. Also shown are the wind vectors obtained from within the highlighted region. We see a more pronounced and well-defined frontal structure associated with the developing storm as resolution is increased. Further runs made at even higher resolution ($.25°$x$.25°$) showed similar features to the $0.5°$x$0.5°$ simulation, showing a convergence of solution.

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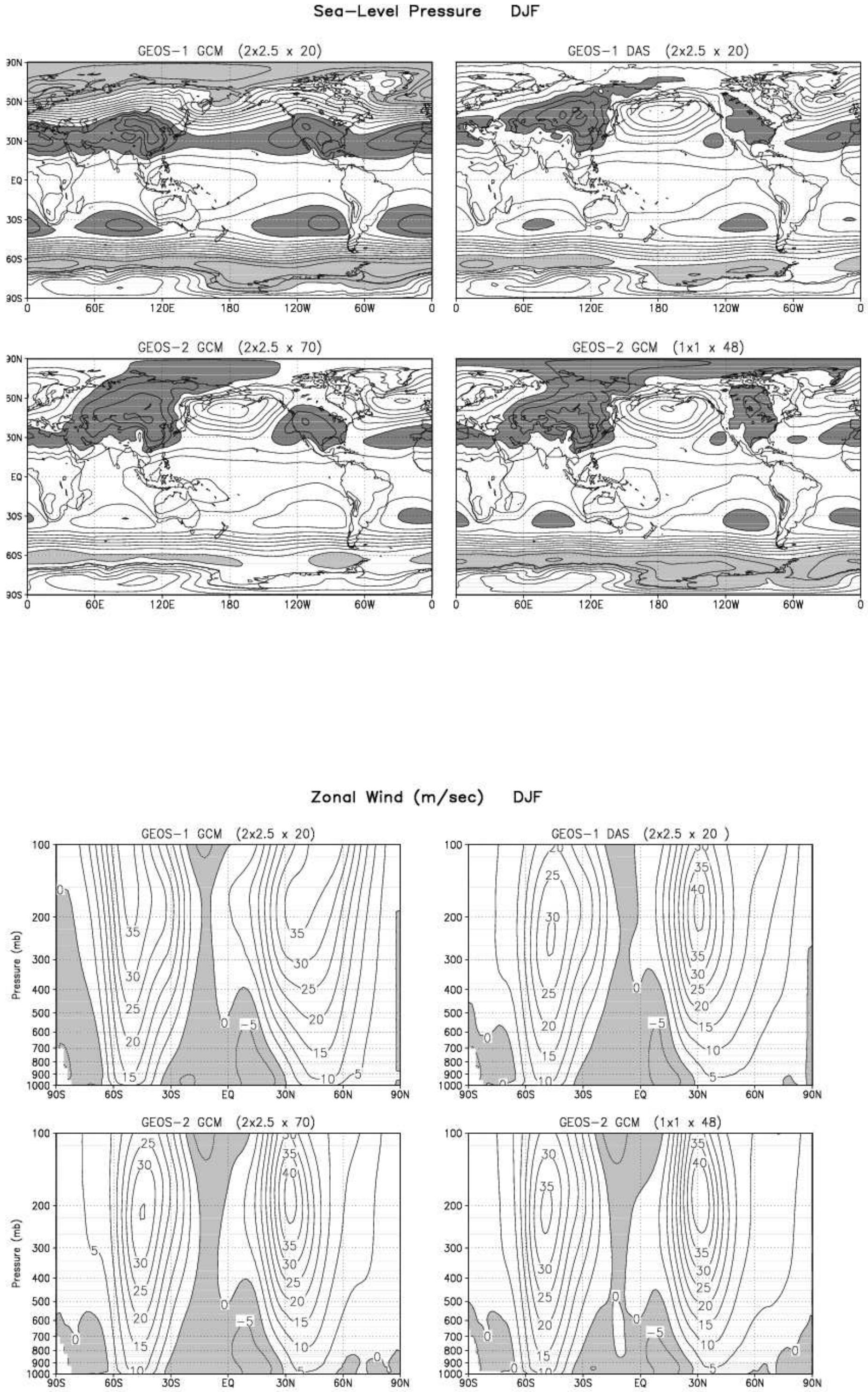

Figure 1: Comparison of seasonal simulations between GEOS-1 (2°x2.5° x 20 Levels), GEOS-2 (2°x2.5° x 70 Levels), GEOS-2 (1°x1° x 48 Levels), and the GEOS-1 DAS Re-Analysis.

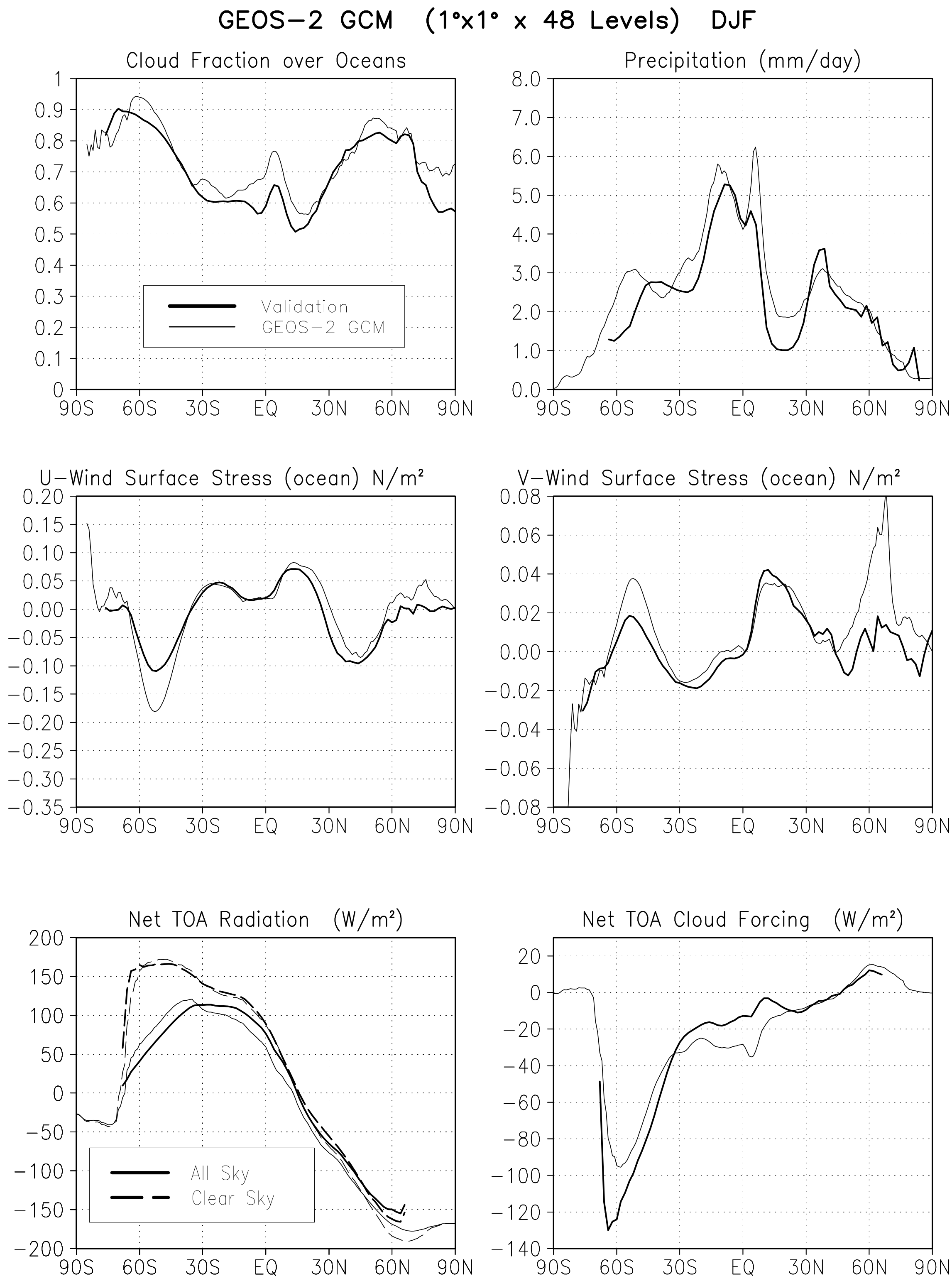

Figure 2: Comparison of seasonal zonal mean quantities from GEOS-2 (1°x1° x 48 Levels) compared with independent observations.

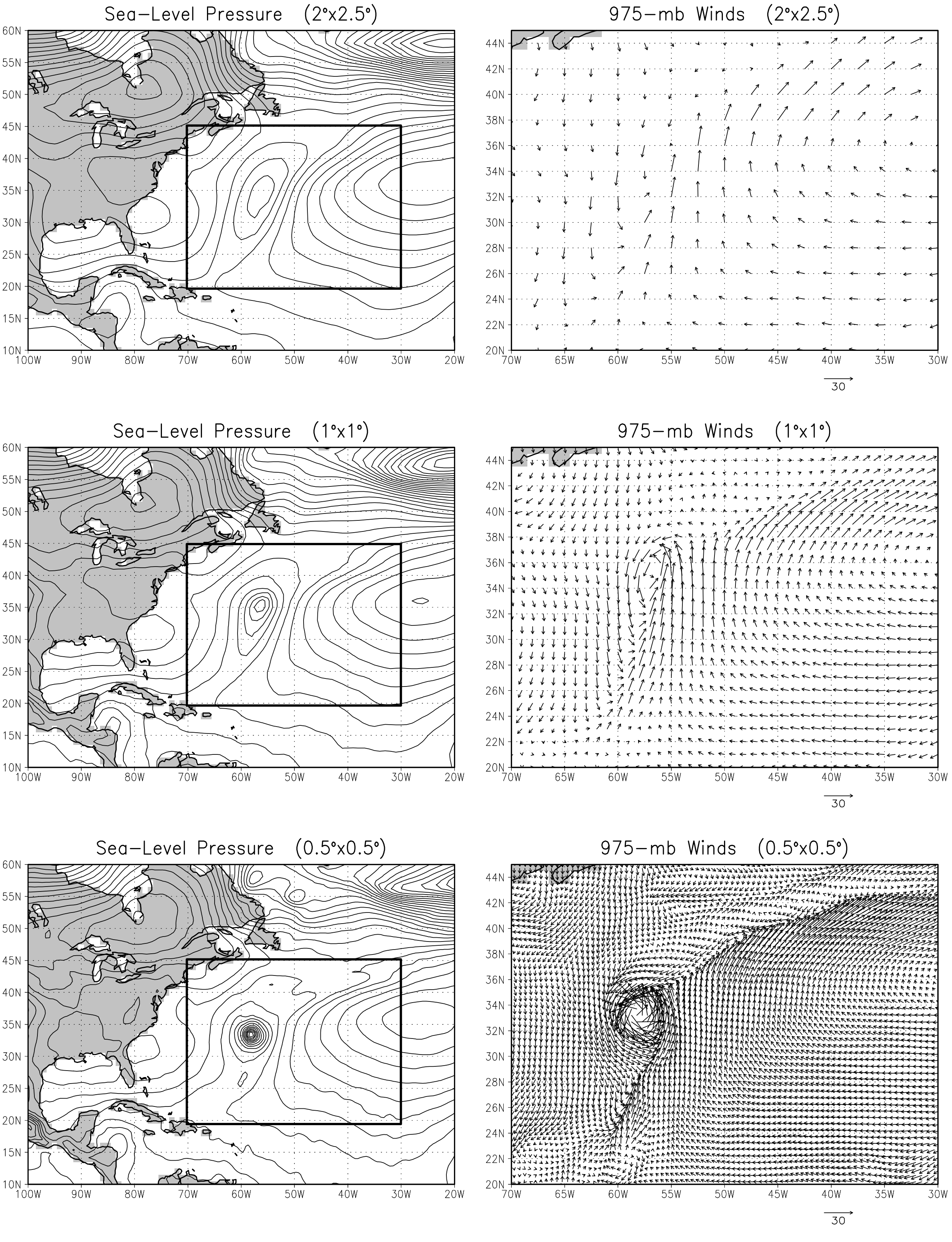

Figure 3: 53-hour forecast using (2°x2.5°), (1°x1°), and (0.5°x0.5°) resolutions.