U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Weather Service
National Centers for Environmental Prediction
4700 Silver Hill Road, Mail Stop 9910
Washington D.C. 20233-9910

NCEP Office Note 442

The GFS Atmospheric Model

Lead Author[1]
Environmental Modeling Center

November 2003

[1]**Corresponding author.** Global Climate and Weather Modeling Branch, EMC, Camp Springs, Maryland

TABLE OF CONTENTS

1. Introduction

This is a brief documentation of the current version of the atmospheric model of NCEP's Global Forecast System (GFS). The GFS model, formerly known as the Medium Range Forecast model (MRF) was initially developed by J. Sela(1980,1982).

The highly detailed original model documentation (NMC Staff, 1988) may be viewed at http://wwwt.emc.ncep.noaa.gov/gmb/wd23ja/doc/web2/tocold1.html.

There has been no update of this to reflect the myriad of changes that have occurred since then. We suggest that interested scientists use the current Office Note and the brief summary noted below to facilitate the use of the model in its present form: http://wwwt.emc.ncep.noaa.gov/gmb/STATS/html/model_changes.html.

This chronological summary contains short descriptions of all changes in the forecast model and in the assimilation/analysis system, as well as references to more complete descriptions found in a series of Office of Meteorology Technical Procedures Bulletins. Another source of information is the published articles referenced below (Caplan, et al.,1997; Kanamitsu, et al.,1991) containing descriptions of major changes and further references to supporting material in the literature. The Environmental Modeling Center intends to provide an updated Technical Note every 2-3 years.

2. Numerical/Computational Properties

2.1 Horizontal Properties

Horizontal Representation: Spectral (spherical harmonic basis functions) with transformation to a Gaussian grid for calculation of nonlinear quantities and physics.

Horizontal Resolution: Spectral triangular 254 (T254); Gaussian grid of 768X384, roughly equivalent to 0.5 X 0.5 degree latitude/longitude.

2.2 Vertical Properties

Vertical Domain: The vertical domain is from the earth's surface (sigma=1) to the top of the atmosphere (sigma=0). This domain is divided into 64 layers with enhanced resolution near the bottom and the top. For a surface pressure of 1000 hPa, the lowest atmospheric level is at a pressure of about 997.3 hPa and the top level is at about 0.27 hPa.

Vertical Representation: Sigma coordinate. Lorenz grid. Quadratic-conserving finite difference scheme by Arakawa and Mintz (1974).

Vertical Resolution: 64 unequally-spaced sigma levels. For a surface pressure of 1000 hPa, 15 levels are below 800 hPa, and 24 levels are above 100 hPa.

2.3 Computer Properties

Computer/Operating System: IBM RS/6000 SP (Class VIII) in an AIX environment.

Computational Performance: About 12 minutes computation time on the IBM per one-day forecast at T254.

2.4 Initialization: Initialization is not necessary because the statistical spectral interpolation analysis scheme eliminates the unbalanced initial state.

2.5 Time Integration Scheme(s): The main time integration is leapfrog for nonlinear advection terms, and semi-implicit for gravity waves and for zonal advection of vorticity and moisture. An Asselin (1972) time filter is used to reduce computational modes. The dynamics and physics are split. The physics are written in the form of an adjustment and executed in sequence. For physical processes, implicit integration with a special time filter (Kalnay and Kanamitsu, 1988) is used for vertical diffusion. In order to incorporate physical tendencies into the semi-implicit integration scheme, a special adjustment scheme is performed (Kanamitsu et al., 1991). The time step is 7.5 minutes for computation of dynamics and physics, except that the full calculation of longwave radiation is done once every 3 hours and shortwave radiation every hour (but with corrections made at every time step for diurnal variations in the shortwave fluxes and in the surface upward longwave flux).

2.6 Smoothing/Filling: Mean orographic heights on the Gaussian grid are used (see Orography). Negative atmospheric moisture values are not filled for moisture conservation, except for a temporary moisture filling that is applied in the radiation calculation.

3. Dynamical/Physical Properties

3.1 Atmospheric Dynamics: Primitive equations with vorticity, divergence, logarithm of surface pressure, specific humidity virtual temperature, and cloud condensate as dependent variables.

3.2 Horizontal Diffusion: Scale-selective, second-order horizontal diffusion after Leith (1971) is applied to vorticity, divergence, virtual temperature, and specific humidity and cloud condensate. The diffusion of temperature, specific humidity, and cloud condensate are performed on quasi-constant pressure surfaces (Kanamitsu et al. 1991).

3.3 Vertical Diffusion: See Planetary Boundary Layer

3.4 Gravity-wave Drag: Gravity-wave drag is simulated as described by Alpert et al. (1988). The parameterization includes determination of the momentum flux due to gravity waves at the surface, as well as at higher levels. The surface stress is a nonlinear function of the surface wind speed and the local Froude number, following Pierrehumbert (1987). Vertical variations in the momentum flux occur when the local Richardson number is less than 0.25 (the stress vanishes), or when wave breaking occurs (local Froude number becomes critical); in the latter case, the momentum flux is reduced according to the Lindzen (1981) wave saturation hypothesis. Modifications are made to avoid instability when the critical layer is near the surface, since the time scale for gravity-wave drag is shorter than the model time step (see also Time Integration Schemes and Orography). The treatment of the gravity-wave drag parameterization in the lower troposphere is improved by the use of the Kim and Arakawa (1995) enhancement. Included is a dependence of variance on wind direction relative to the mountain as well as subgrid statisical details of mountain distribution. This improves the prediction of lee cyclogenesis and the accompanying movement of cold outbreaks (Alpert,et al, 199x).

3.5 Radiation: Longwave radiation follows the simplified exchange method of Fels and Schwarzkopf (1975) and Schwarzkopf and Fels (1991), with calculation over spectral bands associated with carbon dioxide, water vapor, and ozone. Schwarzkopf and Fels (1985) transmission coefficients for carbon dioxide, a Roberts et al. (1976) water vapor continuum, and the effects of water vapor-carbon dioxide overlap and of a Voigt line-shape correction are included. The Rodgers (1968) formulation is adopted for ozone absorption. The cloud emissivity is calculated from the predicted cloud condensate following the approach of the NCAR CCM (Kiehl et al. 1998, Stephens (1984).

The shortwave radiation formulation uses multi-band techniques following the approach of Slingo (1989), Chou et al. (1998) and Kiehl et al. (1998). This formulation includes absorption/scattering by water vapor, ozone, carbon dioxide, clouds, aerosols and oxygen. Data for Rayleigh scattering are calculated from Frohlich and Shaw's formulation (1980). Multiple scattering in clouds is treated using a delta-Eddington approximation with a two-stream adding method (Coakley, etal. 1983). The cloud optical thickness is calculated from the predicted cloud condensate path. This scheme parameterizes the cloud single-scattering properties as a function of effective radius of the cloud condensate. The extinction coefficient, the single-scattering albedo and asymmetry factor for a broad band are parameterized as a linear function of the effective radius. The cloud optical thickness then depends on the extinction coefficient and cloud condensate path. The effective radius for ice is taken as a linear function of temperature decreasing from a value of 80 microns at 263.16 K to 20 microns at temperatures at or below 223.16K. For water droplets with temperatures above 273.16 K an effective radius of 5 microns is used and for supercooled water droplets between the melting point and 253.16 K, a value between 5 and 10 microns is used. (See also Cloud Fraction)

In the present formulation of solar radiation there are seven UV bands, one visible band and a choice of one or three IR bands. Currently one IR-band version is being used for computational economy, but in the future the three-band version may be used. Improved versions of parameterizations of aerosol effects and atmospheric absorption due to oxygen are used in an attempt to reduce solar flux reaching the ground. Horizontal distribution of surface albedo is a function of Matthews (1985) surface vegetation types in a manner similar to Briegleb, et al. (1986). Monthly variation of surface albedo is derived in reference to Staylor and Wilbur (1990).

3.6 Convection: Penetrative convection is simulated following Pan and Wu (1994), which is based on Arakawa and Schubert(1974) as simplified by Grell (1993) and with a saturated downdraft. Convection occurs when the cloud work function exceeds a certain threshold. Mass flux of the cloud is determined using a quasi-equilibrium assumption based on this threshold cloud work function. The cloud work function is a function of temperature and moisture in each air column of the model gridpoint. The temperature and moisture profiles are adjusted towards the equilibrium cloud function within a specified time scale using the deduced mass flux. A major simplification of the original Arakawa-Shubert scheme is to consider only the deepest cloud and not the spectrum of clouds. The cloud model incorporates a downdraft mechanism as well as the evaporation of precipitation. Entrainment of the updraft and detrainment of the downdraft in the sub-cloud layers are included. Downdraft strength is based on the vertical wind shear through the cloud. The critical cloud work function is a function of the cloud base vertical motion. As the large-scale rising motion becomes strong, the cloud work function (similar to CAPE) is allowed to approach zero (therefore approaching neutral stability). Mass fluxes induced in the updraft and the downdraft are allowed to transport momentum. The momentum exchange is calculated through the mass flux formulation in a manner similar to that for heat and moisture. In order to take into account the pressure gradient effect on momentum, a simple parameterization using entrainment is included for the updraft momentum inside the cloud. The entrainment rate, tuned to ensure that the tropical easterly jet strength in the Indian monsoon flow maintains the least drift in the forecast is set to 10^{-4} m^{-1}. This addition to the cumulus parameterization has reduced the feedback between heating and circulation in sheared flows.

In addition, we have made a change in the cloud top selection algorithm in the convection parameterization. In the current SAS scheme, the cloud top level is determined by the parcel method. The level where the parcel becomes stable with respect to the environment is the cloud top. When the prognostic cloud water scheme is tested with this scheme, there is evidence that cloud top detrainment is too concentrated in the upper troposphere. In order to provide a more even detrainment of cloud water in the tropics, we are making a change to the selection algorithm. Once the highest possible cloud top has been determined by the parcel method, we make a random selection of the actual cloud top between the highest possible cloud top and the level where environmental moist static energy is a minimum. The proper entrainment rate is computed to ensure that the parcel becomes neutral at the new cloud top. This is very similar to the Relaxed Arakawa-Schubert (RAS) scheme developed by S. Moorthi. Cloud top detrained water is seperated in to condensate and vapor with the condensate used as a source of prognostic cloud condensate.

3.7 Shallow convection: Following Tiedtke (1983), the simulation of shallow (nonprecipitating) convection is parameterized as an extension of the vertical diffusion scheme. The shallow convection occurs where convective instability exist but no convection occurs. The cloud base is determined from the lifting condensation level and the vertical diffusion is invoked between the cloud top and the bottom. A fixed profile of vertical diffusion coefficients is assigned for the mixing process.

3.8 Cloud Fraction: The fractional area of the grid point covered by the cloud is computed diagnostically following the approach of Xu and Randall (1996) using the formula

$$C = \max[R^{0.25}(1-\exp-\frac{2000x(q_c-q_{cmin})}{\min[\max([(1-R)q^*]^{0.25},0.0001),1.0]}),0.0]$$

where R is the relative humidity, q* is the saturation specific humidity and $q_{cmin}$is a minimum threshold value of q_{min}. The saturation specific humidity is calculated with respect to water phase or ice phase depending on the temperature. Unlike the operational model, the new model has only one type of cloud cover represented by C. In the tropics the cloudiness is primarily due to convective anvils, the result of cumulus detrainment, whereas in the extratropics, cloudiness is mainly through grid-scale condensation.

The fractional cloud cover C is available at all model levels. There is no cloud cover if there is no cloud condensate. Clouds in all layers are assumed to be randomly overlapped. Other options will be explored in the future. (See also Radiation)

3.9 Grid-scale Condensation and Precipitation: The prognostic cloud condensate has two sources, namely convective detrainment (see convection) and grid-scale condensation. The grid-scale condensation is based on Zhao and Carr(1997), which in turn is based on Sundqvist et al. (1989). The sinks of cloud condensate are grid-scale precipitation which is parameterized following Zhao and Carr (1997) for ice, and Sundqvist et al. (1989) for liquid water, and evaporation of the cloud condensate which also follows Zhao and Carr (1997). Evaporation of rain in the unsaturated layers below the level of condensation is also taken into account. All precipitation that penetrates the bottom atmospheric layer is allowed to fall to the surface (see also Snow Cover).

3.10 Planetary Boundary Layer: A new scheme based on the Troen and Mahrt (1986) paper was implemented on 25 October, 1995. The scheme is still a first-order vertical diffusion scheme. There is a diagnostically determined pbl height that uses the bulk-Richardson approach to iteratively estimate a pbl height starting from the ground upward. Once the pbl height is determined, the profile of the coefficient of diffusivity is specified as a cubic function of the pbl height. The actual values of the coefficients are determined by matching with the surface-layer fluxes. There is also a counter-gradient flux parameterization that is based on the fluxes at the surface and the convective velocity scale. (See Hong and Pan(1996) for a description of the scheme as well as a description of the convection scheme in the model).

3.11 Orography: New orography data sets are constructed based on a United States Geological Survey (USGS) global digital elevation model (DEM) with a horizontal grid spacing of 30 arc seconds (approximately 1 km). Orography statistics including average height, mountain variance, maximum orography, land-sea-lake masks are directly derived from a 30-arc second DEM for a given resolution. See NCEP Office Note 424 (Hong, 1999) for more details. (see also Gravity-wave Drag).

3.12 Ocean: A 7-day running mean sea surface temperature analysis is used. The analysis is available once a day at 00GMT. Sea surface temperature anomaly is damped with an e-folding time of 90 days during the course of the forecast.

3.13 Sea Ice: Sea-ice is obtained from the analysis by the marine Modeling Branch, available daily. The sea ice is assumed to have a constant thickness of 3 meters, and the ocean temperature below the ice is specified to be 271.2 K. The surface temperature of sea ice is determined from an energy balance that includes the surface heat fluxes (see Surface Fluxes) and the heat capacity of the ice. Snow accumulation does not affect the albedo or the heat capacity of the ice.

3.14 Snow Cover: Snow cover is obtained from an analysis by NESDIS (the IMS system) and the Air Force, updated daily. When the snow cover analysis is not available, the predicted snow in the data assimilation is used. Precipitation falls as snow if the temperature at sigma=.85 is below 0 C. Snow mass is determined prognostically from a budget equation that accounts for accumulation and melting. Snow melt contributes to soil moisture, and sublimation of snow to surface evaporation. Snow cover affects the surface albedo and heat transfer/capacity of the soil, but not of sea ice. See also Sea Ice, Surface Characteristics, Surface Fluxes, and Land Surface Processes.

3.15 Surface Characteristics: Roughness lengths over oceans are determined from the surface wind stress after the method of Charnock (1955). Over sea ice the roughness is a uniform 0.01 cm. Roughness lengths over land are prescribed from data of Dorman and Sellers (1989) which include 12 vegetation types. Note that the surface roughness is not a function of orography. Over oceans the surface albedo depends on zenith angle. The albedo of sea ice is a function of surface skin temperature and nearby atmospheric temperature as well as snow cover (Grumbine, 1994), with values ranging from 0.65-0.8 for snow-covered sea ice and from 0.45-0.65 for bare sea ice. Albedoes for land surfaces are based on Matthews (1985) surface vegetation distribution (See Radiation). Longwave emissivity is prescribed to be unity (black body emission) for all surfaces. Soil type and Vegetation type data base from GCIP is used. Vegetation fraction monthly climatology based on NESDIS NDVI 5-year climatology is used.

3.16 Surface Fluxes: Surface solar absorption is determined from the surface albedos, and longwave emission from the Planck equation with emissivity of 1.0 (see Surface Characteristics). The lowest model layer is assumed to be the surface layer (sigma=0.996) and the Monin-Obukhov similarity profile relationship is applied to obtain the surface stress and sensible and latent heat fluxes. The formulation was based on Miyakoda and Sirutis (1986) and has been modified by P. Long in the very stable and very unstable situations. A bulk aerodynamic formula is used to calculate the fluxes once the turbulent exchange coefficients have be obtained. Roughness length over ocean is updated with a Charnock formula after surface stress has been obtained. Thermal roughness over the ocean is based on a formulation derived from TOGA COARE(Zeng et al, 1998). Land surface evaporation is comprised of three components: direct evaporation from the soil and from the canopy, and transpiration from the vegetation. The formulation follows Pan and Mahrt (1987).

3.17 Land Surface Processes: Soil temperature and soil volumetric water content are computed in two layers at depths 0.1 and 1.0 meters by a fully implicit time integration scheme (Pan and Mahrt, 1987). For sea ice, the layer depths were specified as 1.5 and 3 meters. Heat capacity, thermal and hydraulic diffusivity and hydraulic conductivity coefficients are strong functions of the soil moisture content. A climatological deep-soil temperature is specified at the third layer of 4 meters for soil and a constant value of 272 K is specified as the ice-water interface temperature for sea ice. The vegetation canopy is allowed to intercept precipitation and re-evaporation. Runoff from the surface and drainage from the bottom layer are also calculated.

3.18 Chemistry: Ozone is a prognostic variable that is updated in the analysis and transported in the model. The sources and sinks of ozone are computed using zonally averaged seasonally varying production and destruction rates provided by NASA/GSFC.

4. References

Alpert, J.C. , C-Y. Hong and Y-J. Kim: 1996, Sensitivity of cyclogenesis to lower troposphere enhancement of gravity wave drag using the EMC MRF, Proc. 11 NWP Conf. Norfolk, 322-323.

Alpert, J.C., M. Kanamitsu, P.M. Caplan, J.G. Sela, G.H. White, and E. Kalnay, 1988: Mountain induced gravity wave drag parameterization in the NMC medium-range model. Preprints of the Eighth Conference on Numerical Weather Prediction, Baltimore, MD, American Meteorological Society, 726-733.

Arakawa, A. and W. H. Shubert, 1974: Interaction of a Cumulus Ensemble with the Large-Scale Environment, Part I. J. Atmos. Sci., 31, 674-704.

Asselin, R., 1972: Frequency filter for time integrations. Mon. Wea. Rev., 100, 487-490.

Betts, A.K., S.-Y. Hong and H.-L. Pan, 1996: Comparison of NCEP-NCAR Reanalysis with 1987 FIFE data. Mon. Wea. Rev., 124, 1480-1498

Briegleb, B. P., P. Minnus, V. Ramanathan, and E. Harrison, 1986: Comparison of regional clear-sky albedo inferred from satellite observations and model computations. J. Clim. and Appl. Meteo., 25, 214-226.

Campana, K. A., Y-T Hou, K. E. Mitchell, S-K Yang, and R. Cullather, 1994: Improved diagnostic cloud parameterization in NMC's global model. Preprints of the Tenth Conference on
Numerical Weather Prediction, Portland, OR, American Meteorological Society, 324-325.

Caplan, et al, 1997: Changes to the 1995 NCEP Operational Medium-Range
Forecast Model. Wea. Forecasting, 12, 581-594.

Charnock, H., 1955: Wind stress on a water surface. Quart. J. Roy. Meteor. Soc., 81, 639-640.

Chen, F., K. Mitchell, J. Schaake, Y. Xue, H.-L. Pan, V. Koren, Q. Y. Duan, M. Ek, and A.

Betts, 1996: Modeling of land surface evaporation by four schemes and comparison with FIFE observations. J. Geophys. Res., 101, D3, 7251-7268.

Chou, M-D, 1990: Parameterizations for the absorption of solar radiation by O2 and CO2 with application to climate studies. J. Climate, 3, 209-217.

Chou, M-D, 1992: A solar radiation model for use in climate studies. J. Atmos. Sci., 49, 762-772.

Chou, M-D and K-T Lee, 1996: Parameterizations for the absorption of solar radiation by water vapor and ozone. J. Atmos. Sci., 53, 1204-1208.

Chou, M.D., M. J. Suarez, C. H. Ho, M. M. H. Yan, and K. T. Lee, 1998: Parameterizations for cloud overlapping and shortwave single scattering properties for use in general circulation and cloud ensemble models. J. Climate, 11, 202- 214.

Coakley, J. A., R. D. Cess, and F. B. Yurevich, 1983: The effect of tropospheric aerosols on the earth's radiation budget: a parameterization for climate models. J. Atmos. Sci., 42, 1408-1429.

Dorman, J.L., and P.J. Sellers, 1989: A global climatology of albedo, roughness length and stomatal resistance for atmospheric general circulation models as represented by the Simple Biosphere model (SiB). J. Appl. Meteor., 28, 833-855.

Fels, S.B., and M.D. Schwarzkopf, 1975: The simplified exchange approximation: A new method for radiative transfer calculations. J. Atmos. Sci., 37, 2265-2297.

Frohlich, C. and G. E. Shaw, 1980: New determination of Rayleigh scattering in the terrestrial atmosphere. Appl. Opt., 14, 1773-1775.

Grell, G. A., 1993: Prognostic Evaluation of Assumprions Used by Cumulus Parameterizations. Mon. Wea. Rev., 121, 764-787.

Grumbine, R. W., 1994: A sea-ice albedo experiment with the NMC medium range forecast model. Weather and Forecasting, 9, 453-456.

Hong, S.-Y. and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a medium-range forecast model. Mon. Wea. Rev., 124, 2322-2339.

Hong, S.-Y., 1999: New global orography data sets. NCEP Office Note #424.

Hou, Y-T, K. A. Campana and S-K Yang, 1996: Shortwave radiation calculations in the NCEP's global model. International Radiation Symposium, IRS-96, August 19-24, Fairbanks, AL.

Joseph, D., 1980: Navy 10' global elevation values. National Center for Atmospheric Research notes on the FNWC terrain data set, 3 pp.

Kalnay, E. and M. Kanamitsu, 1988: Time Scheme for Stronglyt Nonlinear Damping Equations. Mon. Wea. Rev., 116, 1945-1958.

Kalnay, M. Kanamitsu, and W.E. Baker, 1990: Global numerical weather prediction at the National Meteorological Center. Bull. Amer. Meteor. Soc., 71, 1410-1428.

Kanamitsu, M., 1989: Description of the NMC global data assimilation and forecast system. Wea. and Forecasting, 4, 335-342.

Kanamitsu, M., J.C. Alpert, K.A. Campana, P.M. Caplan, D.G. Deaven, M. Iredell, B. Katz, H.-L. Pan, J. Sela, and G.H. White, 1991: Recent changes implemented into the global forecast system at NMC. Wea. and Forecasting, 6, 425-435.

Kiehl, J.T., J. J. Hack, G. B. Bonan, B. A. Boville, D. L. Williamson, and P. J. Rasch, 1998: The national center for atmospheric research community climate model CCM3. J. Climate, 11,1131-1149.

Kim, Y-J and A. Arakawa, 1995: Improvement of orographic gravity wave parameterization using a mesoscale gravity wave model. J. Atmos. Sci. 52, 11, 1875-1902.

Lacis, A.A., and J. E. Hansen, 1974: A parameterization for the absorption of solar radiation in the Earth's atmosphere. J. Atmos. Sci., 31, 118-133.

Leith, C.E., 1971: Atmospheric predictability and two-dimensional turbulence. J. Atmos. Sci., 28, 145-161.

Lindzen, R.S., 1981: Turbulence and stress due to gravity wave and tidal breakdown. J. Geophys. Res., 86, 9707-9714.

Matthews, E., 1985: "Atlas of Archived Vegetation, Land Use, and Seasonal Albedo Data Sets.", NASA Technical Memorandum 86199, Goddard Institute for Space Studies, New York.

Mitchell, K. E. and D. C. Hahn, 1989: Development of a cloud forecast scheme for the GL baseline global spectral model. GL-TR-89-0343, Geophysics Laboratory, Hanscom AFB, MA.

Miyakoda, K., and J. Sirutis, 1986: Manual of the E-physics. [Available from Geophysical Fluid Dynamics Laboratory, Princeton University, P.O. Box 308, Princeton, NJ 08542.]

NMC Development Division, 1988: Documentation of the research version of the NMC Medium-Range Forecasting Model. NMC Development Division, Camp Springs, MD, 504 pp.

NMC staff, 1988: Documentation of the research version of the NMC medium-range forecasting model. NWS/NCEP, 244 pp. [Available from NCEP/Environmental Modeling Center, 5200 Auth Road, Camp Springs, MD 20746.]

Pan, H-L. and L. Mahrt, 1987: Interaction between soil hydrology and boundary layer developments. Boundary Layer Meteor., 38, 185-202.

Pan, H.-L. and W.-S. Wu, 1995: Implementing a Mass Flux Convection Parameterization Package for the NMC Medium-Range Forecast Model. NMC Office Note, No. 409, 40pp. [Available from NCEP, 5200 Auth Road, Washington, DC 20233]

Pierrehumbert, R.T., 1987: An essay on the parameterization of orographic wave drag. Observation, Theory, and Modelling of Orographic Effects, Vol. 1, Dec. 1986, European Centre for Medium Range Weather Forecasts, Reading, UK, 251-282.

Ramsay, B.H., 1998: The interactive multisensor snow and ice mapping system. Hydrol. Process. 12, 1537-1546.

Roberts, R.E., J.A. Selby, and L.M. Biberman, 1976: Infrared continuum absorption by atmospheric water vapor in the 8-12 micron window. Appl. Optics., 15, 2085-2090.

Rodgers, C.D., 1968: Some extension and applications of the new random model for molecular band transmission. Quart. J. Roy. Meteor. Soc., 94, 99-102.

Schwarzkopf, M.D., and S.B. Fels, 1985: Improvements to the algorithm for computing CO2 transmissivities and cooling rates. J. Geophys. Res., 90, 10541-10550.

Schwarzkopf, M.D., and S.B. Fels, 1991: The simplified exchange method revisited: An accurate, rapid method for computation of infrared cooling rates and fluxes. J. Geophys. Res., 96, 9075-9096.

Sela, J., 1980: Spectral modeling at the National Meteorological Center, Mon. Wea. Rev., 108, 1279-1292.

Sela, J.G., 1982: The NMC Spectral Model, NOAA Technical Report NWS-30, 36 pp.

Slingo, J.M., 1987: The development and verification of a cloud prediction model for the ECMWF model. Quart. J. Roy. Meteor. Soc., 113, 899-927.

Slingo, A., 1989: A GCM parameterization for the shortwave radiative properties pf water clouds. J. Atmos. Sci.,46, 1419-1427.

Stephens, G. L., 1984: The parameterization of radiation for numerical weather prediction and climate models. Mon.Wea. Rew., 112, 826-867.

Staylor, W. F. and A. C. Wilbur, 1990: Global surface albedoes estimated from ERBE data. Preprints of the Seventh Conference on Atmospheric Radiation, San Francisco CA, American Meteorological Society, 231-236.

Sundqvist, H., E. Berge, and J. E. Kristjansson, 1989: Condensation and cloud studies with mesoscale numerical weather prediction model. Mon. Wea. Rev., 117, 1641-1757.

Tiedtke, M., 1983: The sensitivity of the time-mean large-scale flow to cumulus convection in the ECMWF model. ECMWF Workshop on Convection in Large-Scale Models, 28 November-1 December 1983, Reading, England, pp. 297-316.

Troen, I. and L. Mahrt, 1986: A simple model of the atmospheric boundary layer; Sensitivity to surface evaporation. Bound.-Layer Meteor., 37, 129-148

Xu, K. M., and D. A. Randall, 1996: A semiempirical cloudiness parameterization for use in climate models. J. Atmos. Sci., 53, 3084-3102.

Zeng, X., M. Zhao, and R.E. Dickinson, 1998: Intercomparison of bulk aerodynamical algorithms for the computation of sea surface fluxes using TOGA COARE and TAO data. J. Climate, 11, 2628-2644.

Zhao, Q. Y., and F. H. Carr, 1997: A prognostic cloud scheme for operational NWP models. Mon. Wea. Rev., 125,1931-1953.