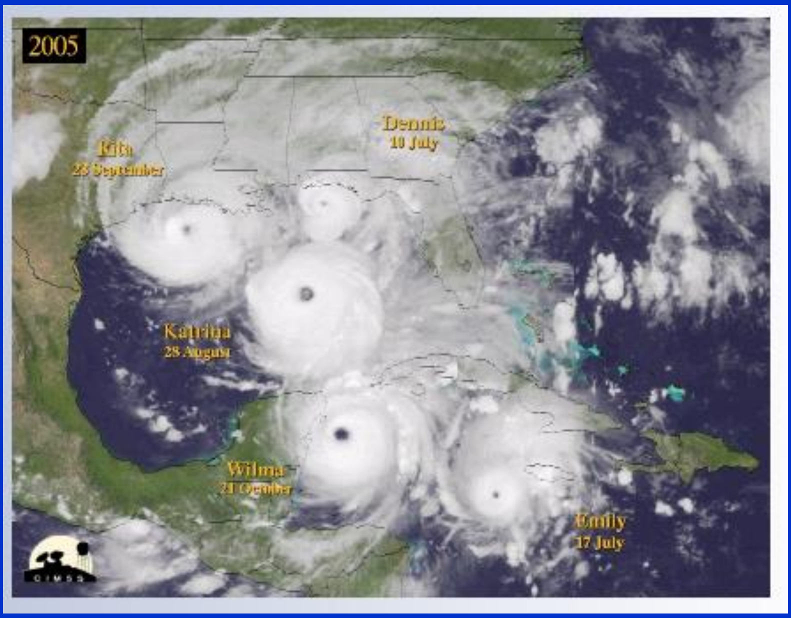
Ch. 1 Introduction and Historical Review of Numerical Weather Prediction



AST 853 (NWP)

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(http://mesolab.org)

1.2 Historical Review of Numerical Weather Prediction (From Ross 1986, in Ray 1986)

- 1904 Bjerknes – Viewed the weather forecasting as an initial-value problem.

- 1922 Lewis Fry Richardson developed the first numerical weather prediction system.
  - Division of space into grid cells and the finite difference approximations of Bjerknes's "primitive differential equations."
  - His own attempt to calculate weather for a single 8-h period using an analysis by Bjerknes for 7am 20 May 1910 as initial condition. It took 6 weeks and ended in failure (predicted 145 mb rise in 6 hours); however, if numerical smoothing is applied, it was quite accurate.
  - His model's enormous calculation requirements led Richardson to propose a solution he called the "forecast-factory."
  - The "factory" would have filled a vast stadium with 64,000 people.
  - Each one, armed with a mechanical calculator, would perform part of the calculation.
  - A leader in the center, using colored signal lights and telegraph communication, would coordinate the forecast.

1.2 Historical Review of Numerical Weather Prediction (Ross 1986, in Ray 1986**)**

- 1928 Courant, Friedricks, and Lewy – Found a stability criterion (later named “*CFL criterion*”) for numerical integration.
- 1939 Rossby – Simplified the governing equations for large scale motion by scale analysis.
- 1950 Charney, Fjotoft, and von Neumann -- Made the first numerical forecasts on the ENIAC based on the Rossby’s barotropic model.

  Only winds on 500 mb were forecasted.
- 1950 Rapid advances in NWP models.
- 1954 Formed the Joint Numerical Weather Forecasting Unit for developing operational versions of research model.

1.2 Historical Review of Numerical Weather Prediction
(Continued)

- 1958 First geostrophic, barotropic model of the Northern Hemisphere was introduced as an objective forecasting tool for National Weather Service (NWS).

- 1962 A 3-level baroclinic filtered-equation model became operational.

- 1966 A 6-level, hemispheric, primitive equation (PE) model became operational.

- 1971 The Limited-area Fine-Mesh (LFM) model was introduced in National Meteorological Center (NMC).

  The horizontal resolution in North America is significantly increased.

  The Nested-Grid Model (NGM) became operational later.

- 1980 The grid-point hemispheric PE model was replaced by a 12-level global spectral model that predicts large-scale features for periods of 5-10 days.

- 1980- Developments of the <u>ETA model at NMC</u> and the <u>ECMWF models at ECMWF</u>.

1.3 Developments of NWP Models at NCEP

(Kalnay 2003)

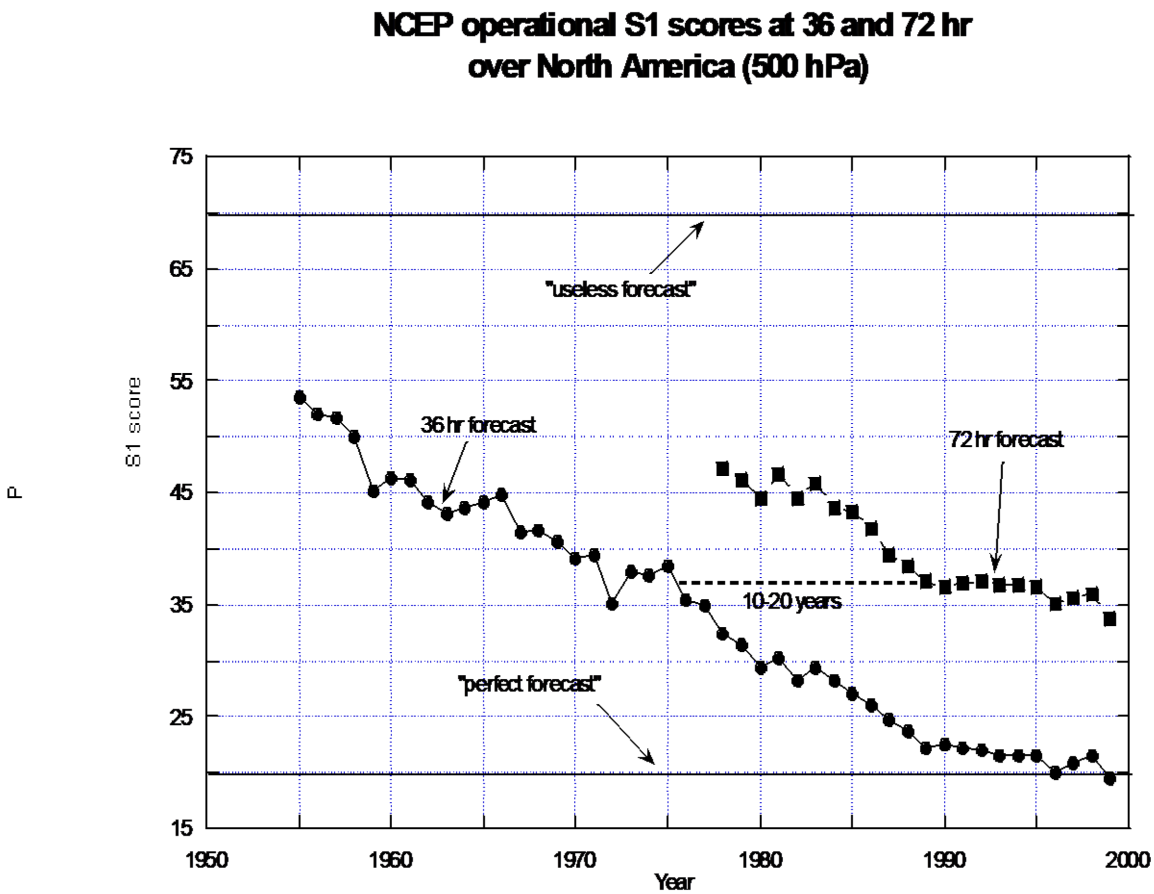


Fig. 1.1a (Kalnay 2003) shows the longest available record of the skill of numerical weather prediction.

The "S1" score measures the relative error in the horizontal gradient of the isobaric height of 500 mb for a forecast over North America.

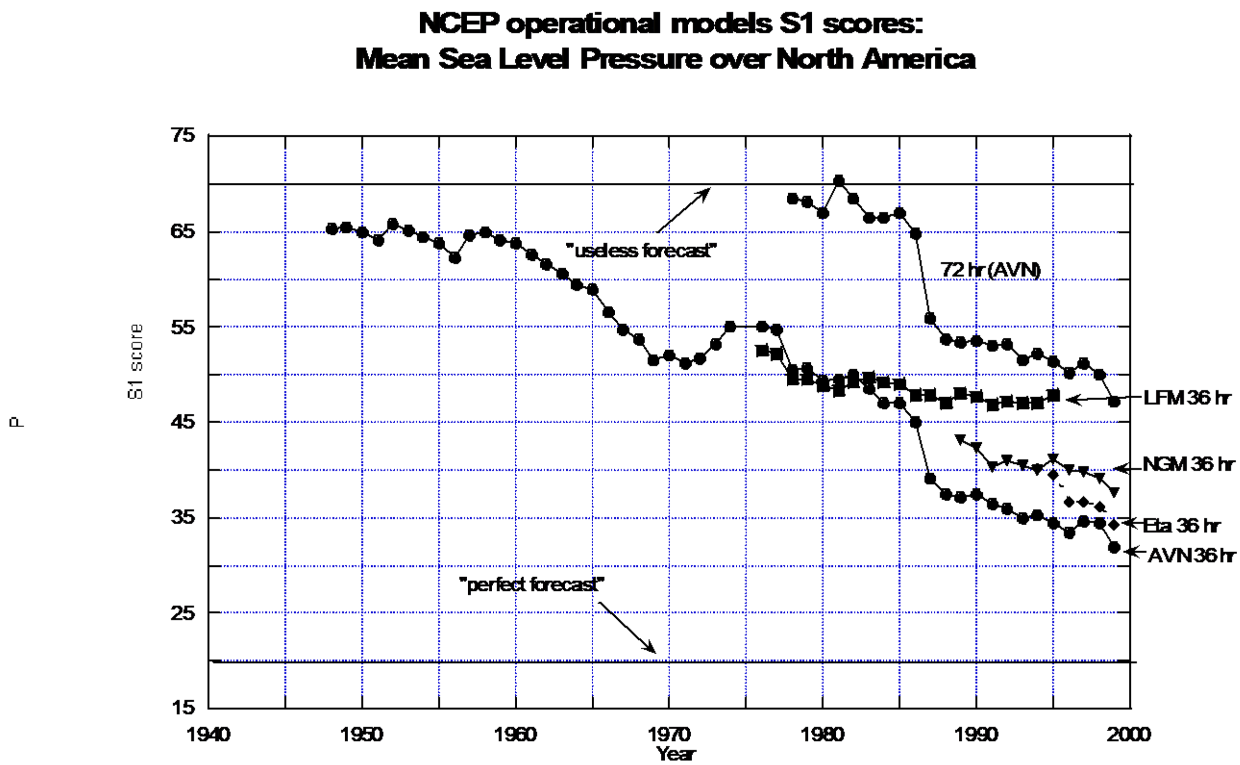
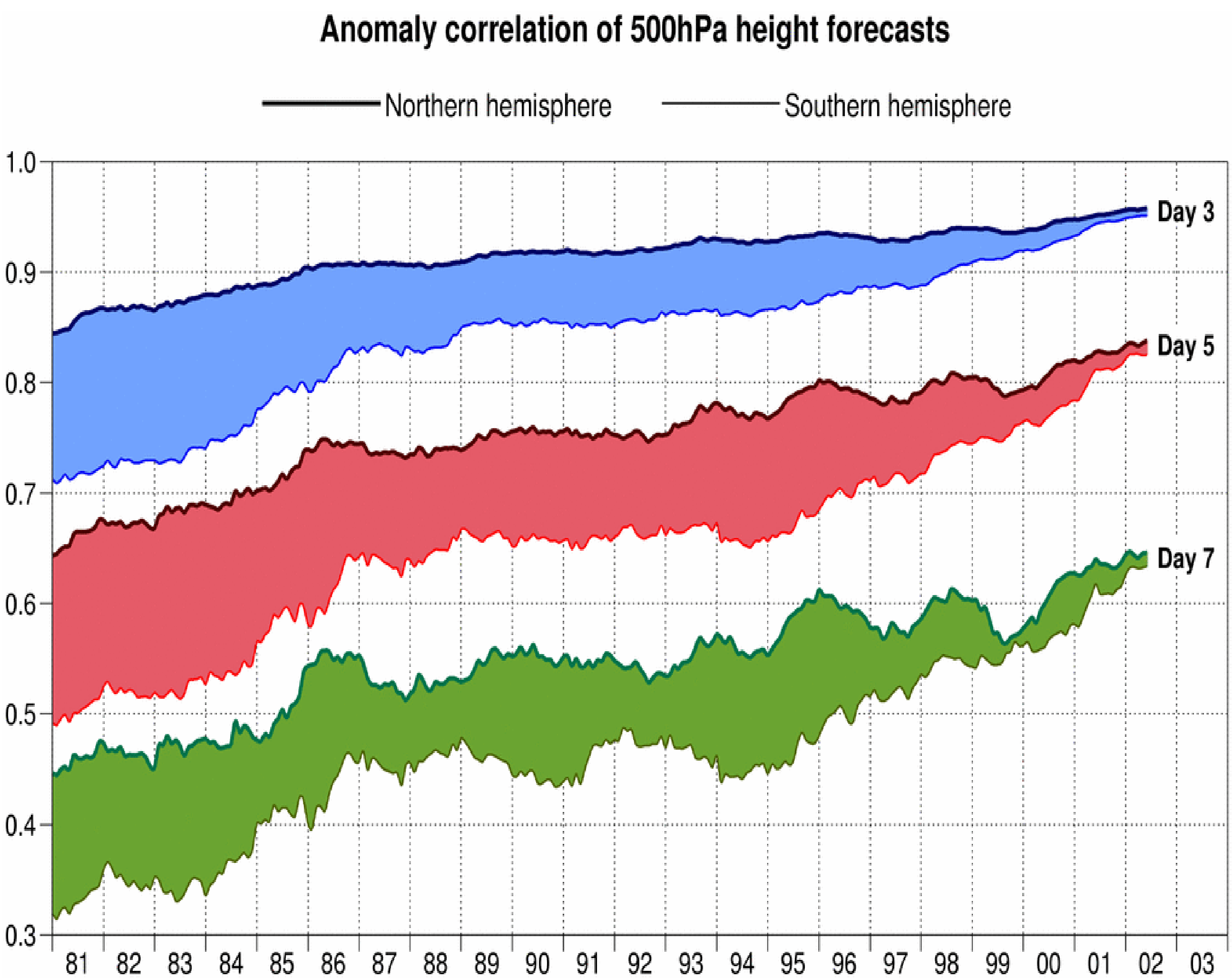


Fig. 1.1b

- The sea level pressure forecasts contain smaller-scale atmospheric structures, and are still difficult to forecast in detail, although their prediction has also improved very significantly over the years, so their S1 score is still well above 20% (Fig.1.1b).

- Five-day forecast had "no skill" 15 years ago, are now moderately skillful.

Forecast Skills for the Northern and Southern Hemispheres



(Hollingsworth et al. 2004)

1.4 Improvement in skill of NWP

- Improved the understanding of the atmospheric dynamics.
- Increased power of supercomputers, allowing much finer numerical resolution and better approximations in the operational atmospheric models.
- Improved representations of small-scale physical processes (clouds, precipitation, turbulent transfers of heat, moisture, momentum, and radiation) within the models.
- Increased availability of data, especially satellite and aircraft data over the oceans and the Southern Hemisphere.
- Use of more accurate methods of data assimilation, which result in improved initial conditions for the models.

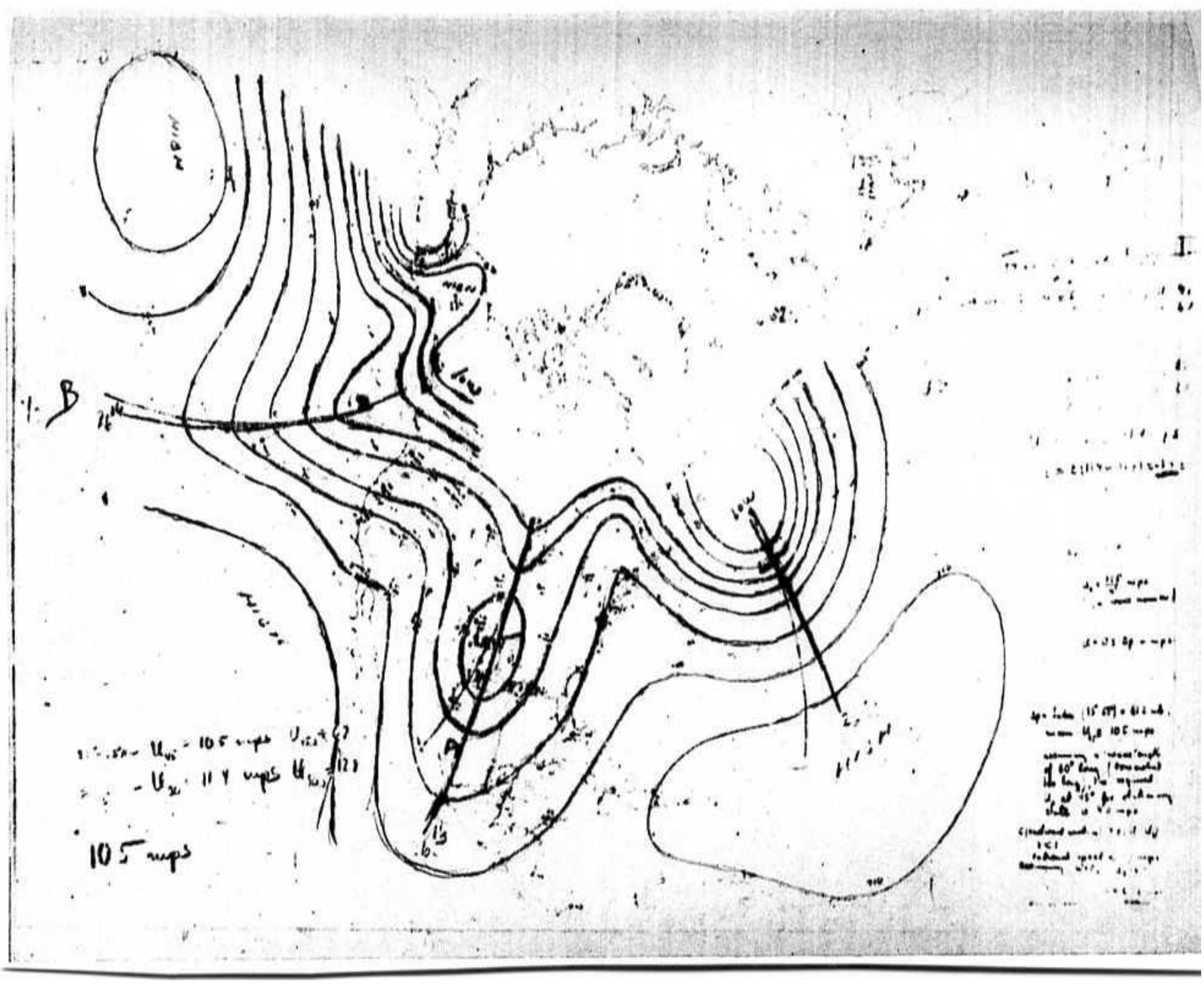
(Based on T.-W. Yu, 2008)

Improved Understanding of Atmospheric Dynamics

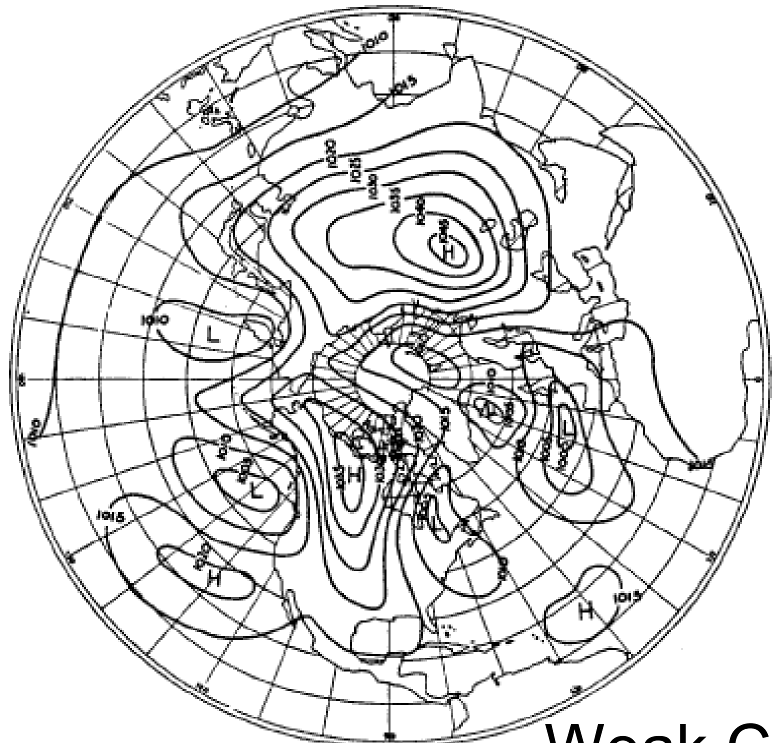
Karl-Gustaf Rossby

FIG. 1. A portrait of Carl-Gustaf Rossby superimposed on a weather map that appeared on the cover of *Time* magazine, 17 December 1956. The editor received three letters from weatherwise readers who spotted inconsistencies on the map (14 January 1957 issue).

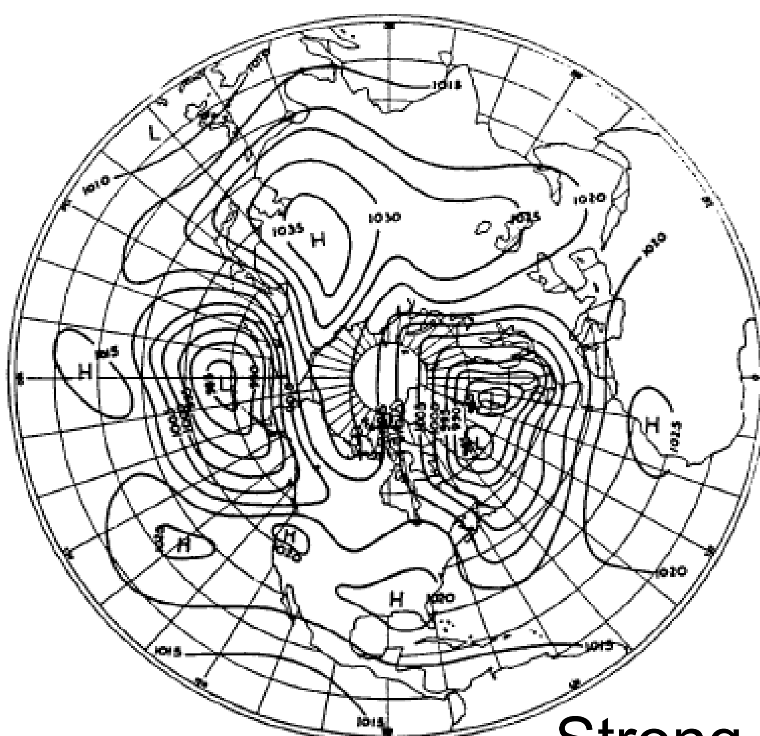
The first application of Rossby Trough Formula
25 December 1940



(Courtesy of J. Namias)



Weak Circulation

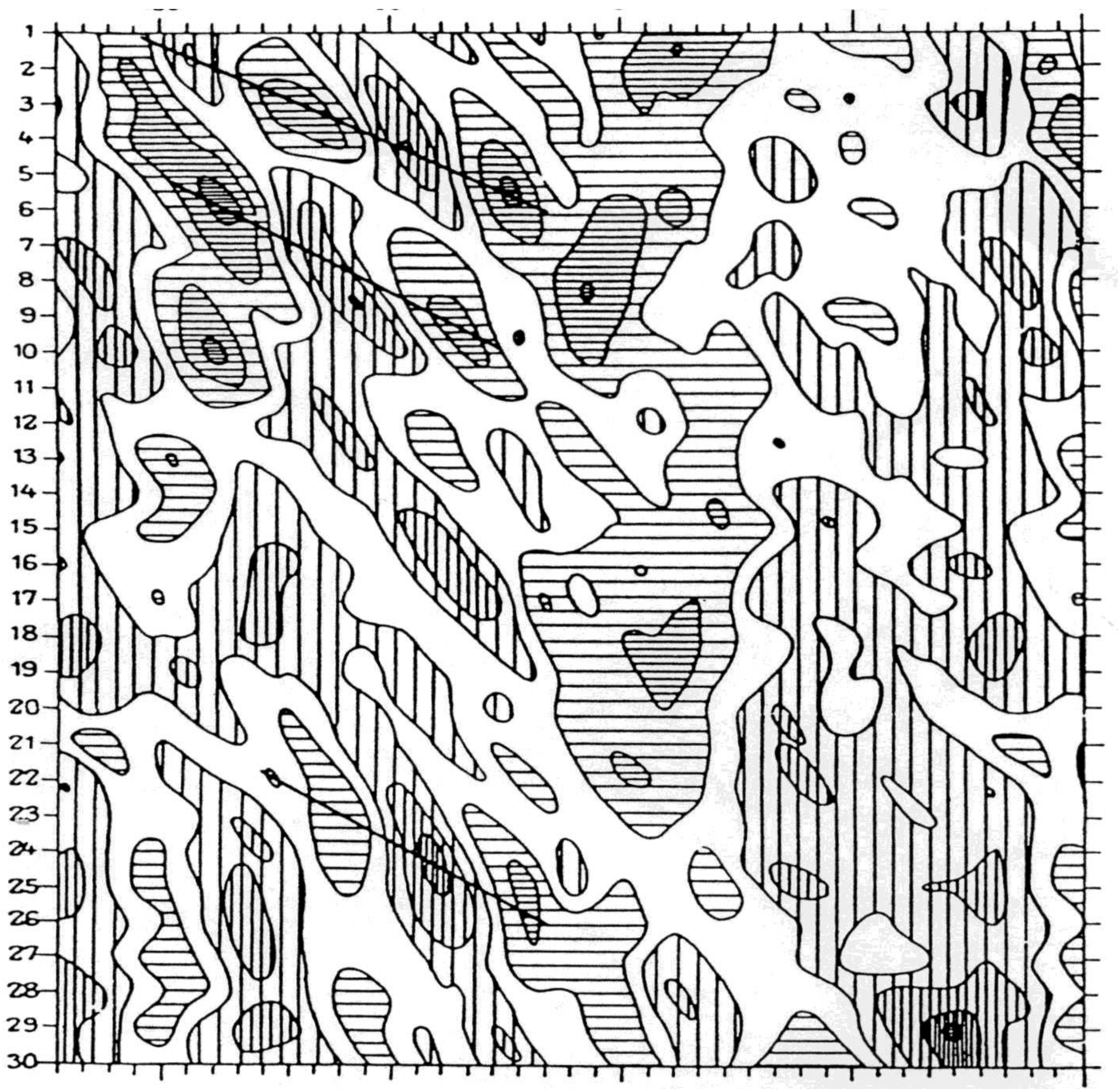


Strong Circulation

Zonal Circulations (Rossby, 1941)

Trough-Ridge Diagram of Hovmöller (1949)
(Hovmoller Diagram)

D
A
Y
S
↓



Longitudes East →

Geophysical Fluid Dynamics Equations Used

$$\frac{\partial U}{\partial t} = - \frac{C_s}{h} \frac{\partial P}{\partial x} - jW + fV,$$

$$\frac{\partial V}{\partial t} = - \frac{C_s}{h} \frac{\partial P}{\partial y} - fU,$$

$$\frac{\partial W}{\partial t} = - C_s \left(\frac{\partial P}{\partial z} + \Gamma P \right) + jU + N^2 Q,$$

$$\frac{\partial P}{\partial t} = - C_s \left(\nabla_3 \cdot \boldsymbol{U} - \Gamma W \right),$$

$$\frac{\partial Q}{\partial t} = - W.$$

(From Hydrodyn. Oceans and Atmos. -Carl Eckart, 1960)

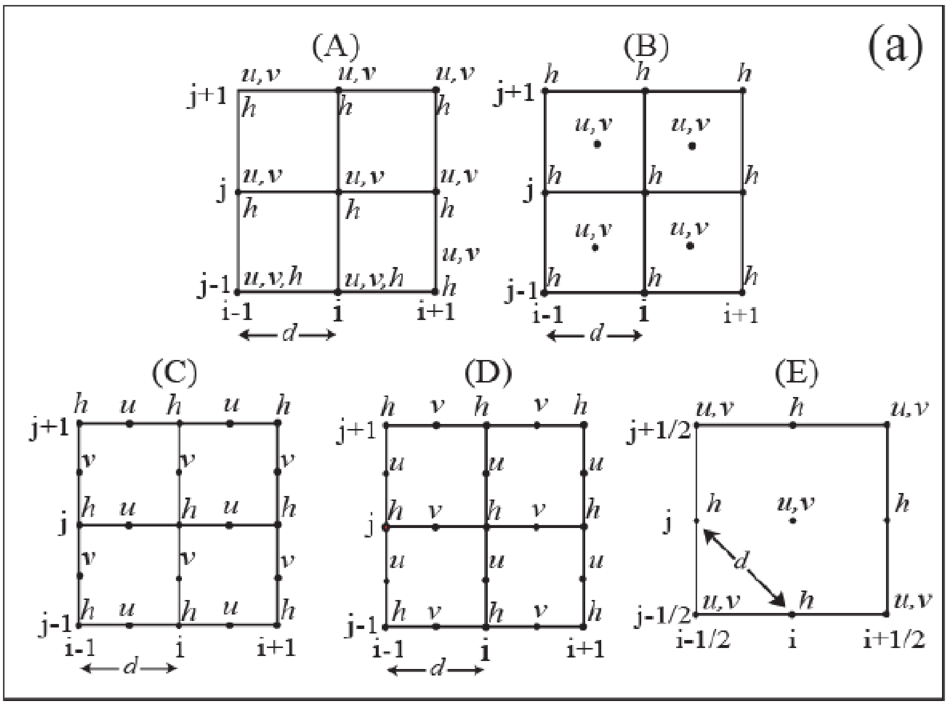
Increased Supercomputing Power

Table 1: Major operational implementations and computer acquisitions at NMC between 1955 and 1985 (Shuman, 1989)

1955:	3-level QG Model	IBM 701
1958:	Barotropic Model	IBM 704
1962:	Improved 3-Level QG Model	IBM 7090
1966:	6-Layer PE Model	CDC 6600
1971:	LFM	
1978:	7-Layer PE model	IBM 360
1980:	Global Spectral model (12 layers)	Cyber 205
1985:	Nested Grid Model (NGM)	
	….	
1990		Cray YMP (8cpu/32MW)
1994		Cray C90 (16cpu/128MW)
1998		IBM SV2 (256 processors)

Better Numerical Methods

Arakawa Five Grid Layout Systems



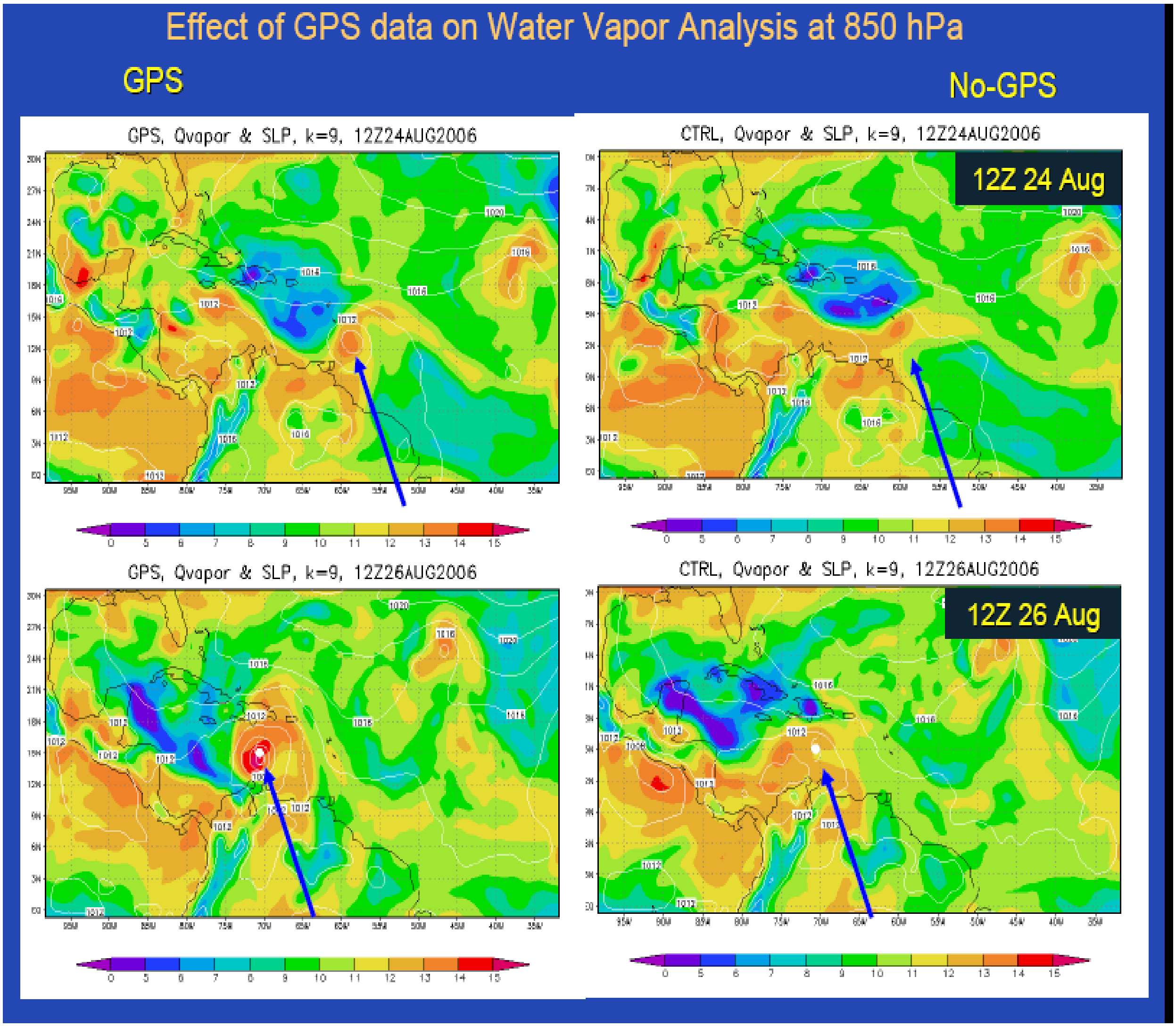
(Arakawa 1964; Fig. 13.7 of Lin 2007)

A Grid – Un-staggered system between wind and mass fields

B, C, D, & E –Grids Staggered system

Each grid system has different numerical properties associated with it.

Initialization of NWP models using satellite data



(After Liu et al. NCAR, 2008)

Increased availability of data

Evolution of Global Data Base

a. First Decade (1955 – 1965)

- Radiosonde reports – only N.H.
- Aircraft data – a few, not reliable
- Surface obs. - a few thousand land stations, but less than 20 ships
- 1960 TIROS-1 was launched

b. Second Decade (1966 – 1975)

- ATS-1 (Application Technology Satellite)
- Geostationary satellite providing imagery and cloud-tracked winds
- Nimbus Infrared Radiometer temperature profile data

c. Third Decade (1976 – 1985)

- Increase in aircraft data (ASDAR, ACAR)
- Increase in satellite data (1978 Seasat – measure ocean surface winds, waves, temp., sea ice, etc.; 1978-79 FGGE year data - TIROS Series, temp. profile data)

d. Fourth Decade (1986 – 1996)

1986 – Wind profile data
1986 – VAS temperature and humidity data
1987 – Geosat altimeter ocean wind and wave and sea ice data
1987 – DMSP SSM/I ocean wind speed and temperature and sea ice data
1991 – ERS-1 (ESA) scatterometer winds
1996 – ERS-2 (ESA) scatterometer winds
1996 – Lidar radial wind data
1997 – NSCAT ocean surface winds

e. Fifth Decade (1996 – 2005)

- Substantial increase in DMSP products – SSM/I winds and precipitable water
- 5-order magnitude increase in satellite data over 10 years

1999 – NASA QuikSCAT Scatterometer
winds, sea ice, and etc.,

2003 – Meteo-SAT

2003 – Aqua (EOS) – MODIS and TRIMM

2008 – NPOSS

1.5 Developments in mesoscale models and cloud models

(a) Mesoscale research models (Hydrostatic)

- MASS (Kaplan et al. 1982)
- PSU/NCAR MM4 (Anthes et al. 1982; Kuo and Anthes, 1984)
- GFDL models (Orlanski et al. 1983; Orlanski and Polinsky 1984)
- Drexel LAMPS (Kalb 1984; Chang et al. 1984)
- Hurricane Research Division Model
- CSU Mesoscale Model (Pielke et al.)
- Australian CSIRO model (Physick et al.)
- French MC2 model (Blondin et al.)
- NMC models
- Naval Environmental Research Facility model;
- NOAA/ERL model
- UK Meteorological Office Mesoscale Model
- Other models developed in universities and research centers

(b) Cloud Model (nonhydrostatic)

- Wilhelmson and Klemp model
- Schlesinger model
- Orville model
- Cotton model
- Clark Model
- TASS
- Other models

(c) Hybrid Mesoscale-Cloud Model (nonhydrostatic)

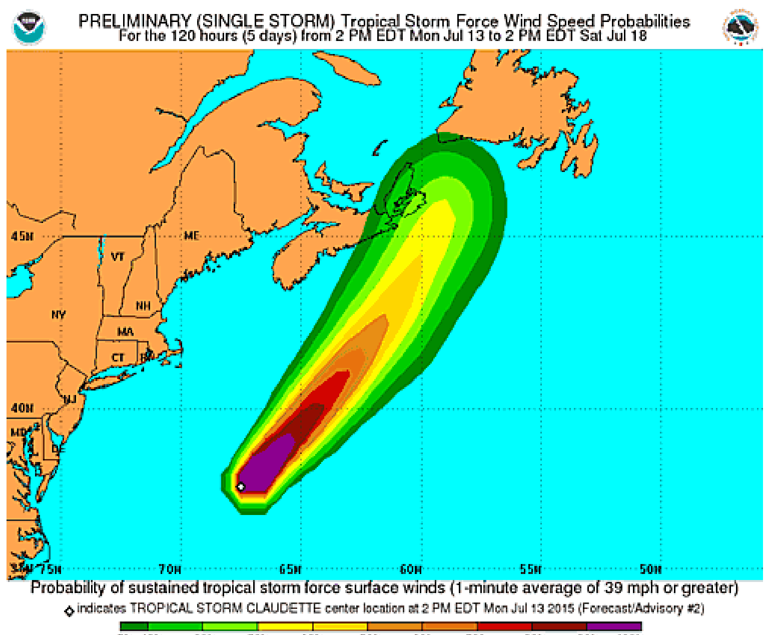
- CSU-RAMS model
- PSU/NCAR MM5 model
- ARPS model (OU)
- COAMPS (navy)
- MC2 (Canada)
- NH-Meso (France)
- NH-MASS (Meso Inc., NCSU)
- NTU-Purdue Model
- WRF (Weather Research and Forecast) model
- Other models

(d) Global-Model NWP

NWP goes global – Using global models to make regional numerical weather prediction.

Next Generation

Global Prediction System (NGGPS)



Fred Toepfer, NGGPS Project Manager

(4 August 2015)

NGGPS Over-Arching Objectives

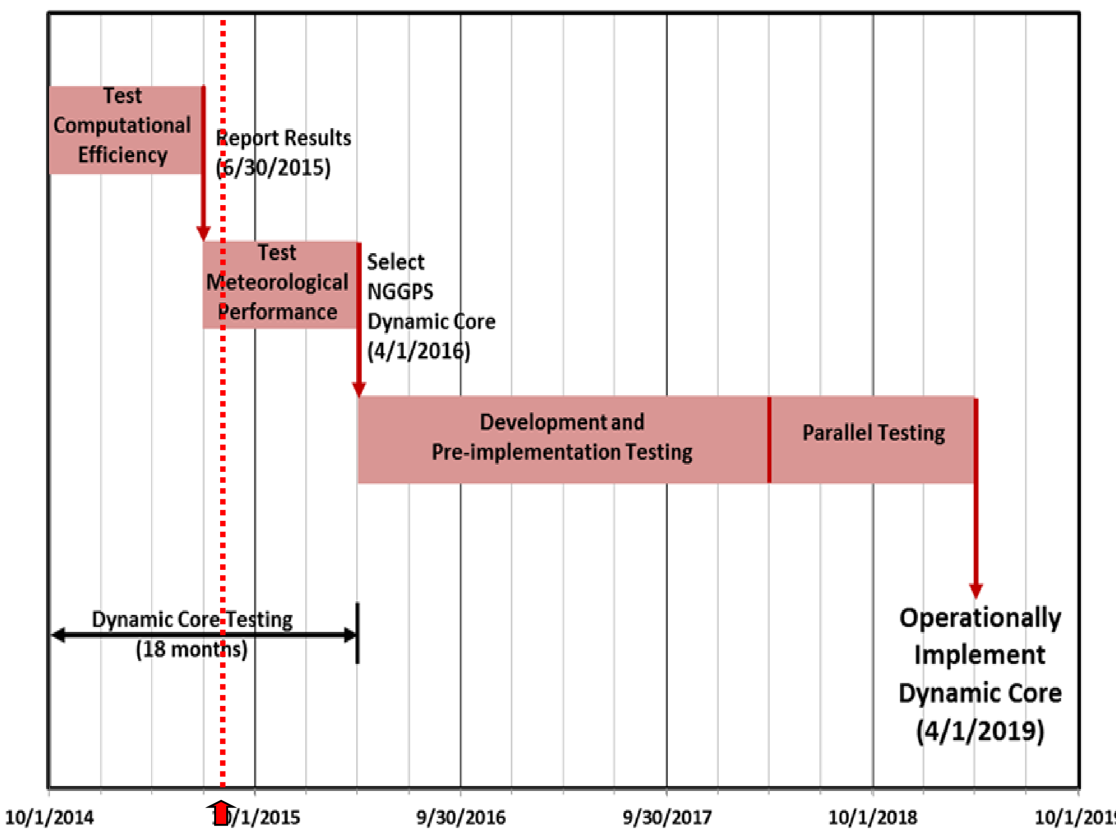
- Re-establish US as the World leader in Global Weather Prediction
  - Extend forecast skill beyond 8 to 10 days
  - Improve hurricane track and intensity forecast
- Extend Weather Forecast to 30 days
  - Implement a weather-scale, fully-coupled NWP System - Atmosphere, Ocean, Sea Ice, Land Surface, Waves, Aerosols and Atmospheric Composition
  - Support development of products for weeks 3 and 4
- Support unification of the NWS Numerical Weather Prediction Suite
- Multi-year Community Effort
- Position NWS to take advantage of Advanced High Performance Computing Architectures

NGGPS Phase 1 Testing
Project Summary Assessment

	Idealized Tests	3-km, 3-day forecasts	Performance	Scalability	Nesting or Mesh Refinement	Software Maturity
FV3	Green	Green	Green	Green	Green	Green
MPAS	Green	Green	Yellow	Green	Green	Green
NIM	Yellow	Red	Green	Green	Red	Green
NMM-UJ	Red	Yellow	Green	Green	Yellow	Red
NEPTUNE	Yellow	Red	Red	Green	Green	Red

- Green: Meets or exceeds readiness for needed capability
- Yellow: Some capability but effort required for readiness
- Red: Capability in planning only or otherwise insufficiently ready

Atmospheric Dynamic Core Development Schedule



1.6 Definitions of Atmospheric Scales

(see Lin 2007 for a more thorough review)

- Scaling of atmospheric motions is normally based on observational and theoretical considerations.
- The following scaling is often used.
  - Large (synoptic) scale: L > 2000 km
  - Mesoscale: 2 km < L < 2000 km
    - Meso-α : 200 km < L < 2000 km
    - Meso-β : 20 km < L < 200 km
    - Meso-γ : 2 km < L < 20 km
  - Microscale: L < 2 km
- Sometimes it is more meaningful to adopt a Lagrangian time scale rather than a Eulerian time scale (L/U).

Table 1.2 *Lagrangian time scales and Rossby numbers for typical atmospheric systems. (Adapted after Emanuel and Raymond 1984.)*

Phenomenon	Time scale	Lagrangian R_o ($\approx \omega/f = 2\pi/fT$)
Tropical cyclone	$2\pi R/V_T$	V_T/fR
Inertia-gravity waves	$2\pi/N$ to $2\pi/f$	N/f to 1
Sea/land breezes	$2\pi/f$	1
Thunderstorms and cumulus clouds	$2\pi/N_w$	N_w/f
Kelvin–Helmholtz waves	$2\pi/N$	N/f
PBL turbulence	$2\pi h/U^*$	U^*/fh
Tornadoes	$2\pi R/V_T$	V_T/fR

where:
R = radius of maximum wind scale, ω = frequency, T = time scale, V_T = maximum tangential wind scale, f = Coriolis parameter, N = buoyancy (Brunt–Vaisala) frequency, N_w = moist buoyancy (Brunt-Vaisala) frequency, U^* = scale for friction velocity, h = scale for the depth of planetary boundary layer.

Table 1: Atmospheric scale definitions, where L_H is horizontal scale length. (Thunis and Bornstein 1996; in Lin 2007)

L_H	Lifetime	Stull (1988)	Pielke (1984)	Orlanski (1975)	Thunis and Bornstein (1996)	Atmospheric Phenomena
10 000km	1 month	Macro	Synoptic Regional	Macro-α	Macro-α	General circulation, long waves
2000 km	1 week			Macro-β	Macro-β	Synoptic cyclones
200 km	1 day			Meso-α	Macro-γ	Fronts, hurricanes, tropical storms, short cyclone waves, mesoscale convective complexes
20 km		Meso	Meso	Meso-β	Meso-β	Mesocyclones, mesohighs, supercells, squall lines, inertia-gravity waves, cloud clusters, low-level jets thunderstorm groups, mountain waves, sea breezes
2 km	1 h		Micro	Meso-γ	Meso-γ	Thunderstorms, cumulonimbi, clear-air turbulence, heat island, macrobursts
200 m	30 min	Micro		Micro-α	Meso-δ	Cumulus, tornadoes, microbursts, hydraulic jumps
20 m	1 min			Micro-β	Micro-β	Plumes, wakes, waterspouts, dust devils
2 m	1 s			Micro-γ	Micro-γ	Turbulence, sound waves
		Micro-δ			Micro-δ	

1.7 Energy Generation and Scale Interaction

Fig. 1.1: Average kinetic energy of zonal (west-east) wind component in the free atmosphere (Vinnichenko 1970; in Lin 2007)

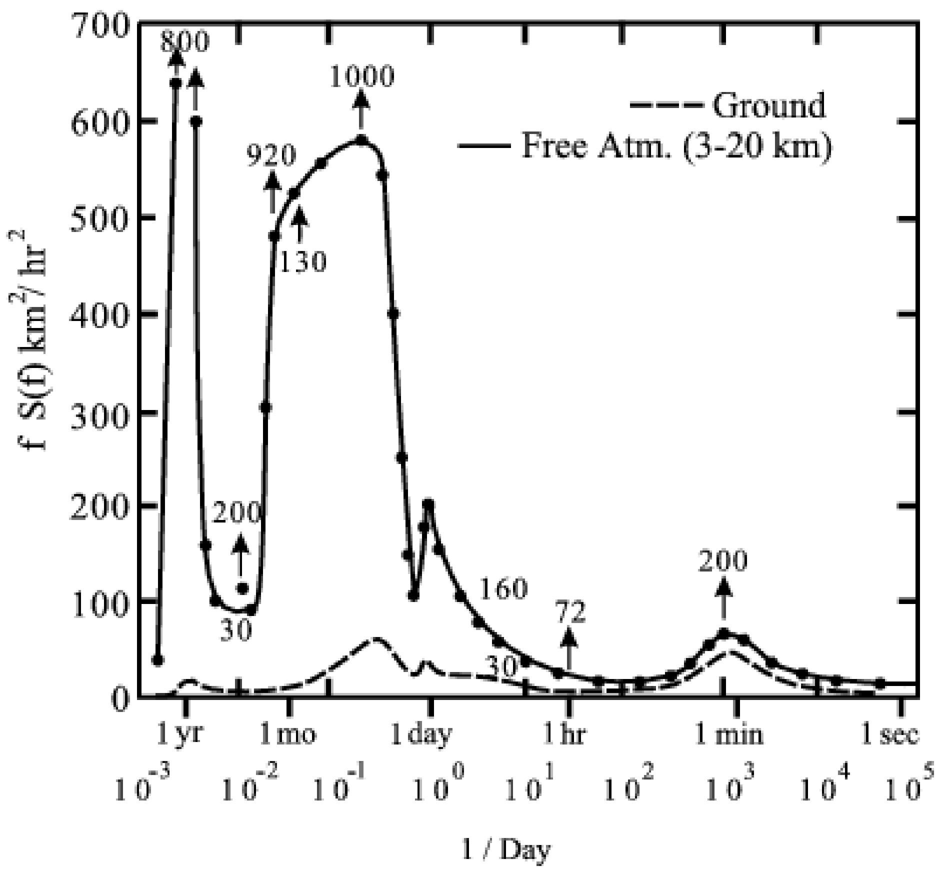
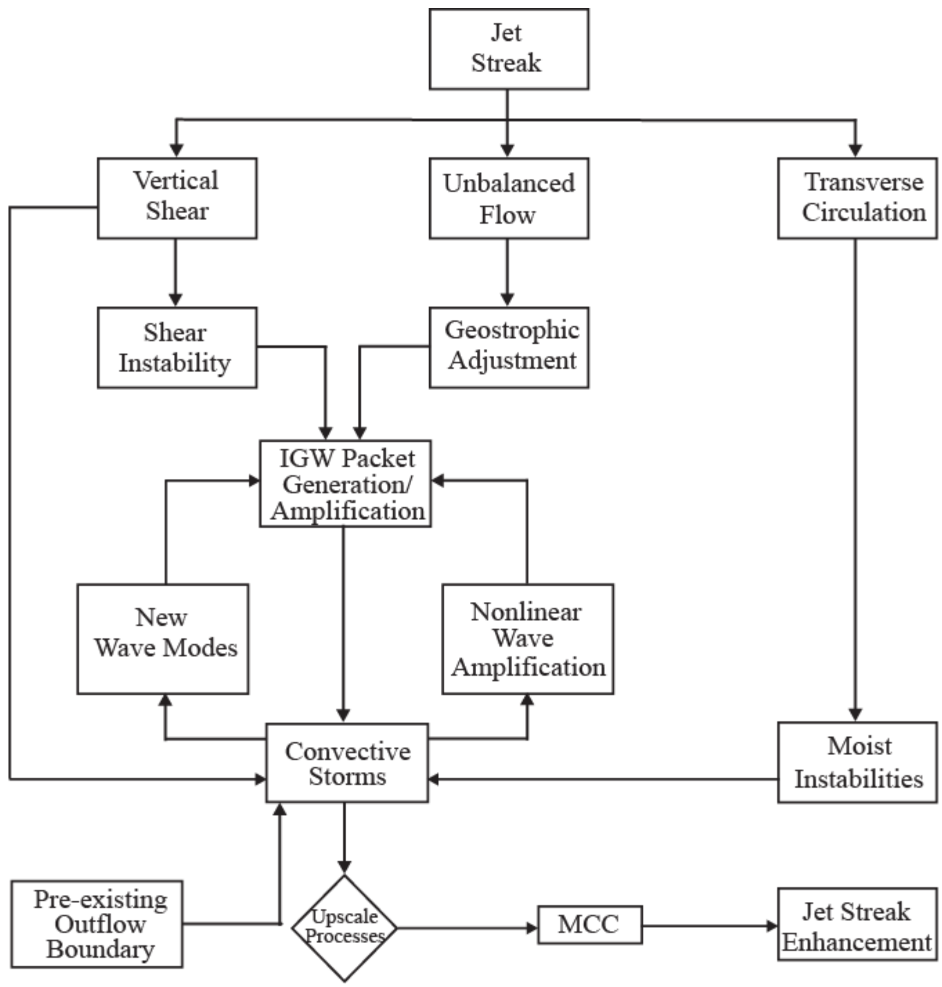


Fig. 1.4: Mutual interactions between the jet streak, inertial-gravity waves, and strong convection (Lin 2007, adapted from Koch 1997)



1.8 Predictability

- The question of predictability of atmospheric phenomena was first investigated by Lorentz (1969) for the interaction of barotropic vorticity perturbations encompassing a number of diverse horizontal scales.

- The response of a fluid system to a steady forcing tends to fall into one of the following four categories (Emanuel and Raymond 1984):

(1) steady for a stable system - perfectly predictable,
(2) periodic for a weakly unstable system - perfectly predictable,
(3) aperiodic with a "lumpy" spectrum for a moderately unstable system - less predictable, or
(4) aperiodic with a monotonic spectrum for a fully turbulent system – rather unpredictable.

- The solutions of weather systems diverge since there is an uncertainty associated with initial conditions determined from real observations.

- Thus, the atmospheric systems fall into category (3). That is, the weather phenomena have *limited predictability.*

- Mesoscale is more predictable than larger scales, because mesoscale phenomena are strongly constrained by topography and other surface features. (Anthes 1985)

  Such constraints may only work when other dynamical processes are weak (Lin 2007).