Atmospheric Motions II
ATM S 442/504

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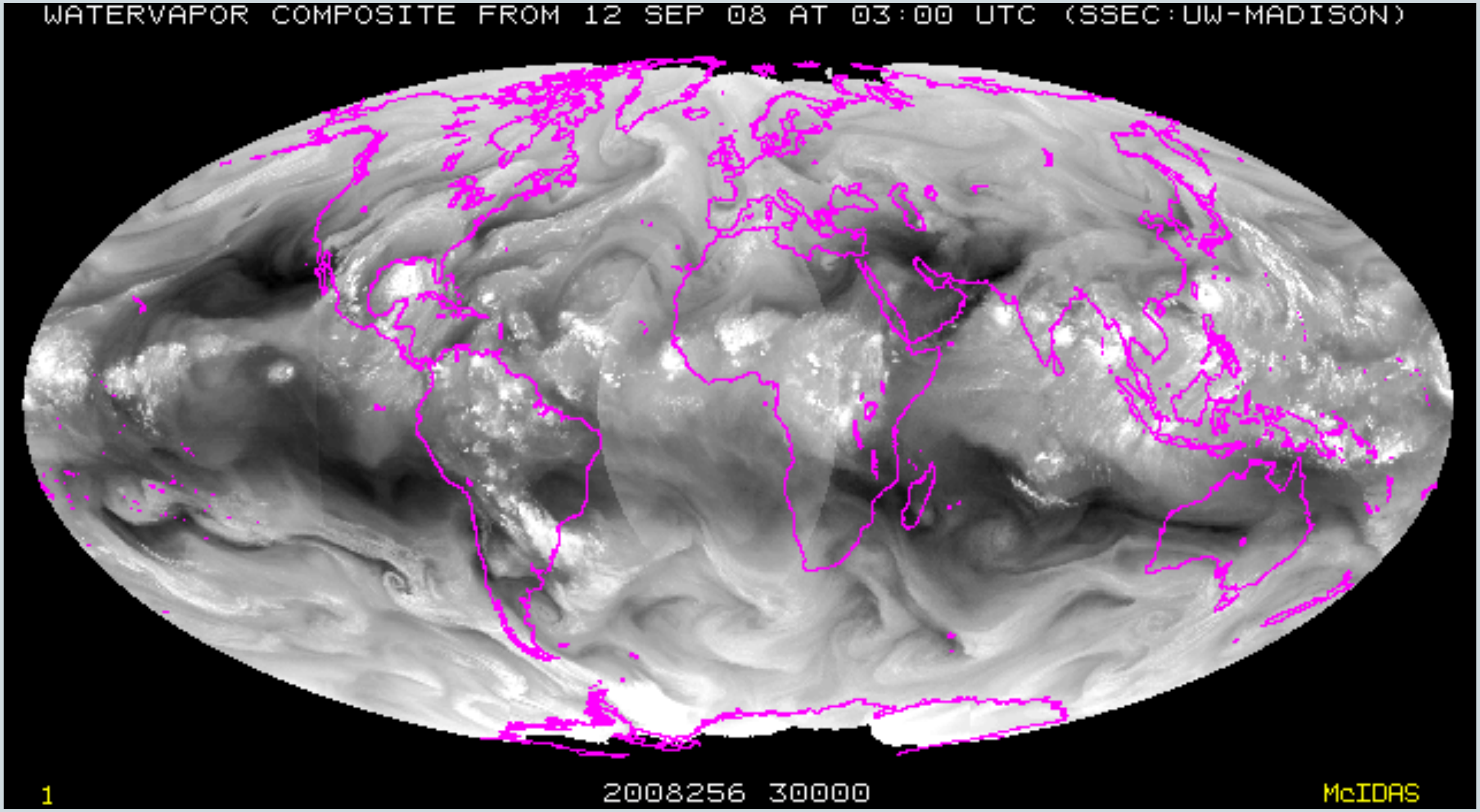
LECTURE 1: JAN 6, 2014

Atmospheric Motions

- Fluid motion on the sphere!

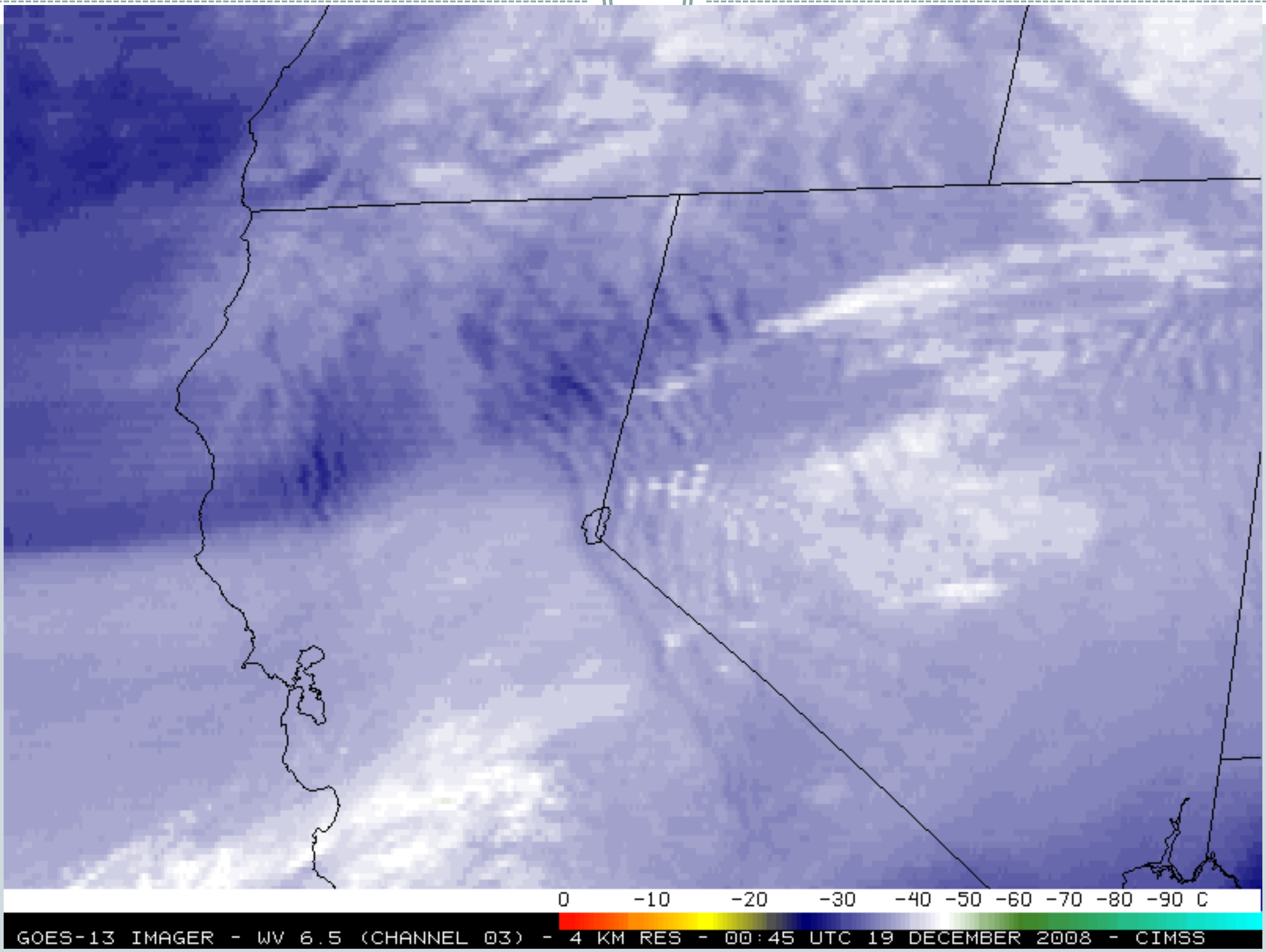


Water vapor global composite (U Wisc)

Class Summary

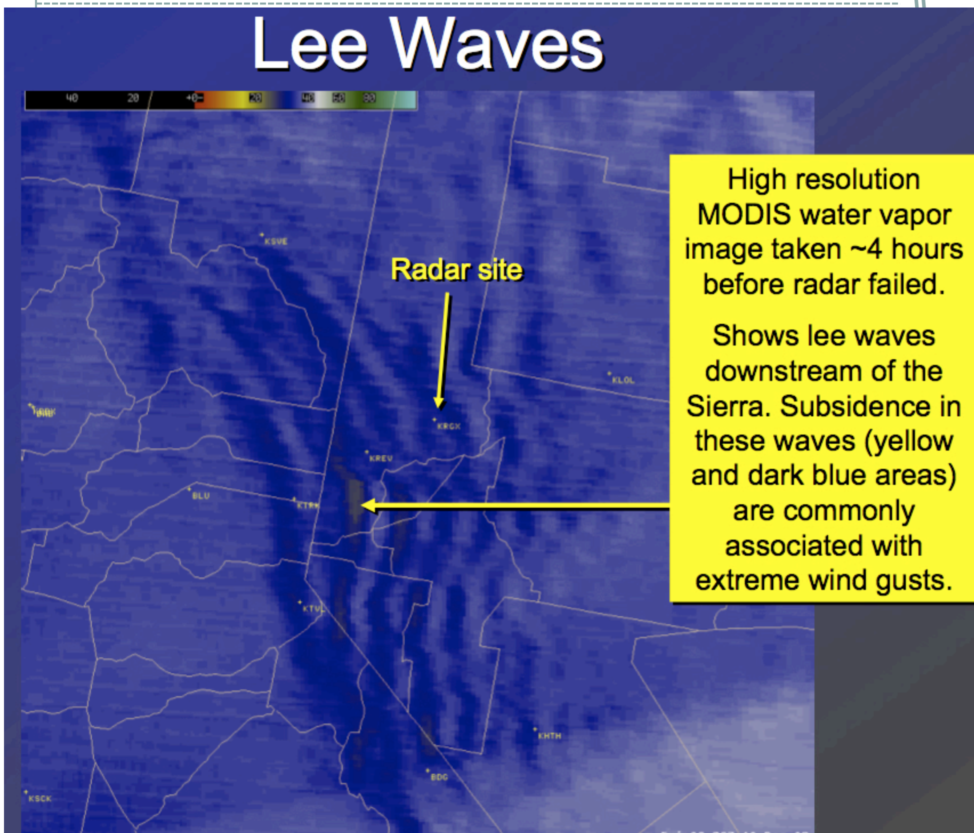
- Looking for ways to interpret atmospheric circulations
  - Understanding of *why* different classes of motions occur

Waves

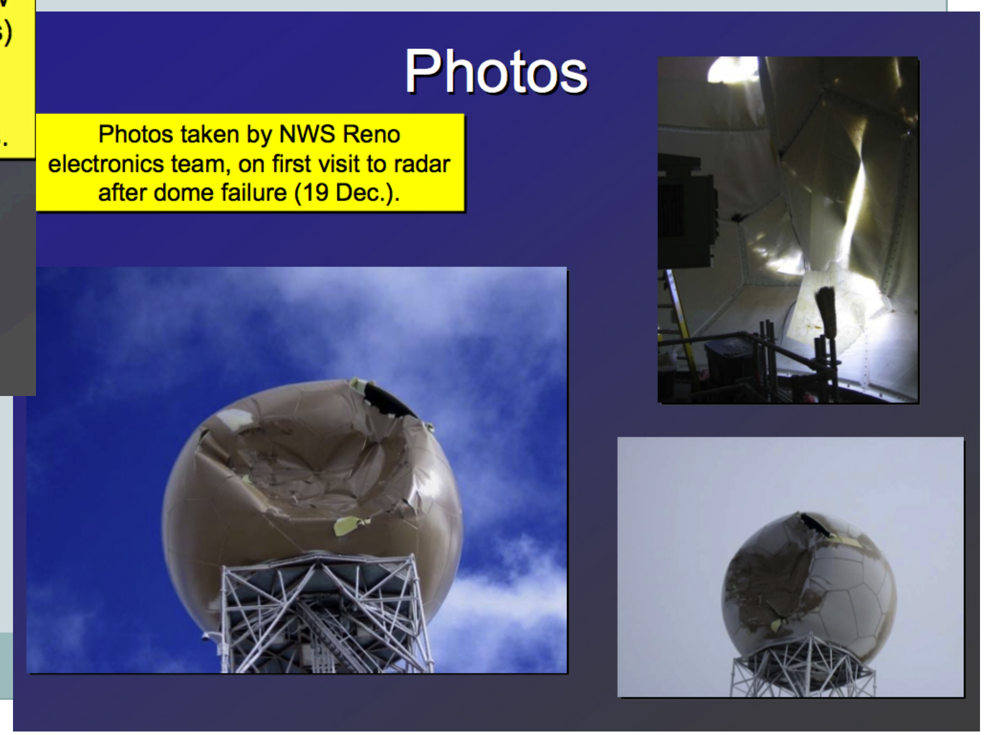


GOES Satellite Image courtesy of CIMSS

Lee Wave Wind Event

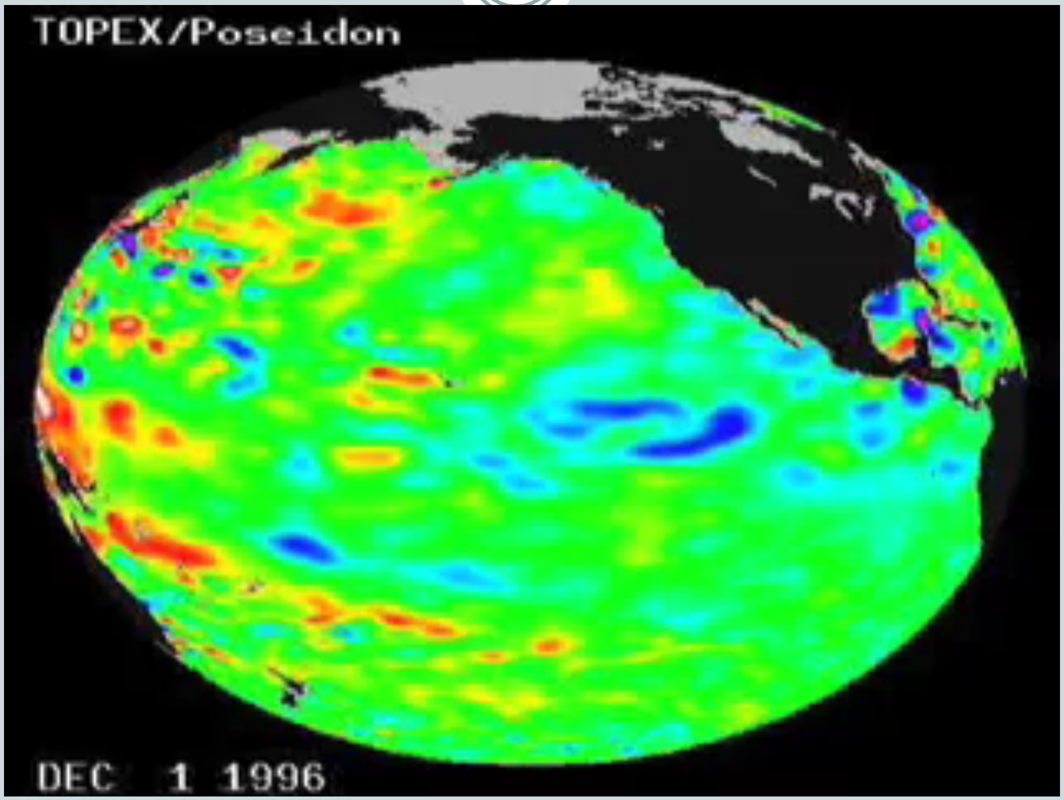


- Dec 19, 2008 in western Nevada
- High winds (140 mph (63 m/s) gusts)
- Damaged the Reno/Virginia Peak NWS radar



Courtesy of NWS Reno

El Nino & Oceanic Equatorial Kelvin Waves



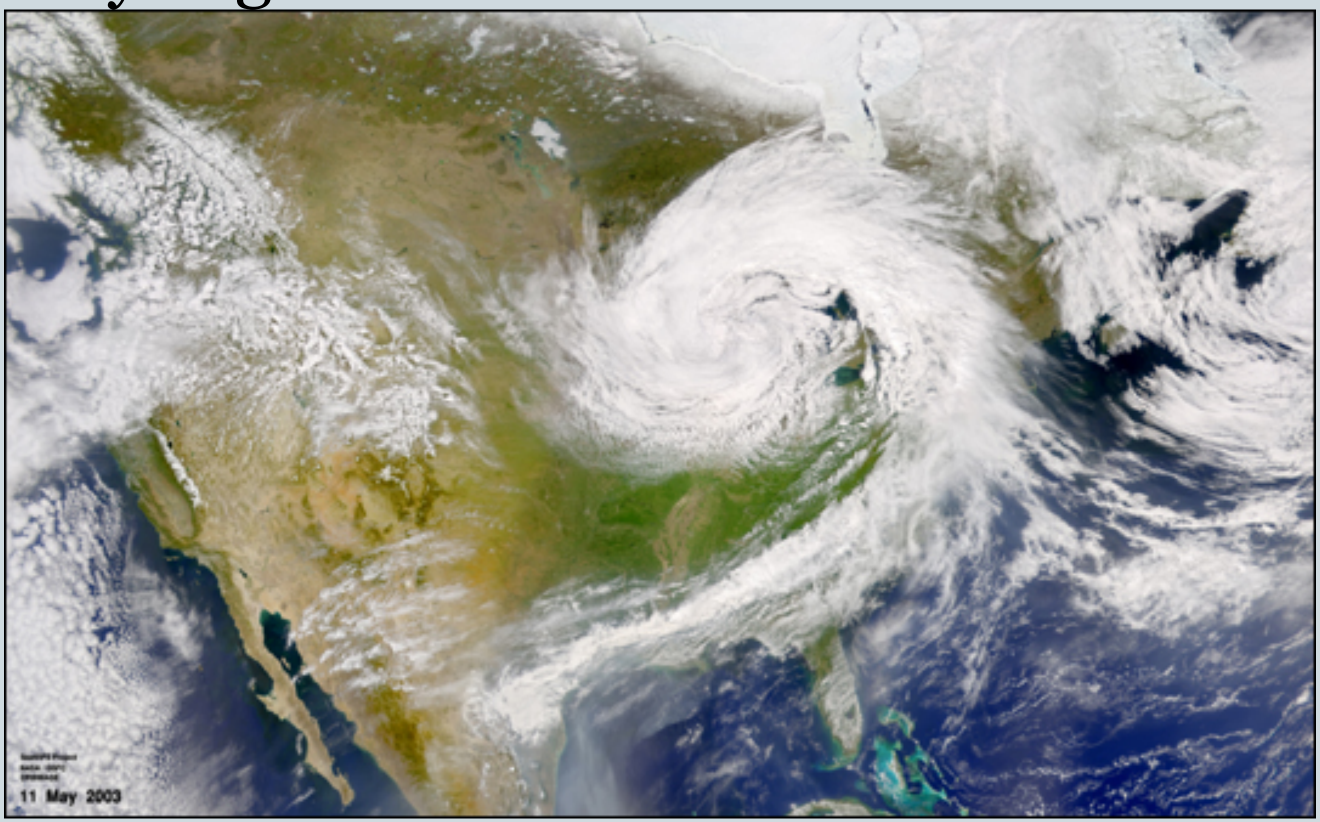
- Kelvin waves in the ocean leading to the development of '97-98 El Nino event
- These waves were excited by Madden-Julian Oscillation events in the atmosphere (which are related to atmospheric Kelvin waves!)

Instabilities

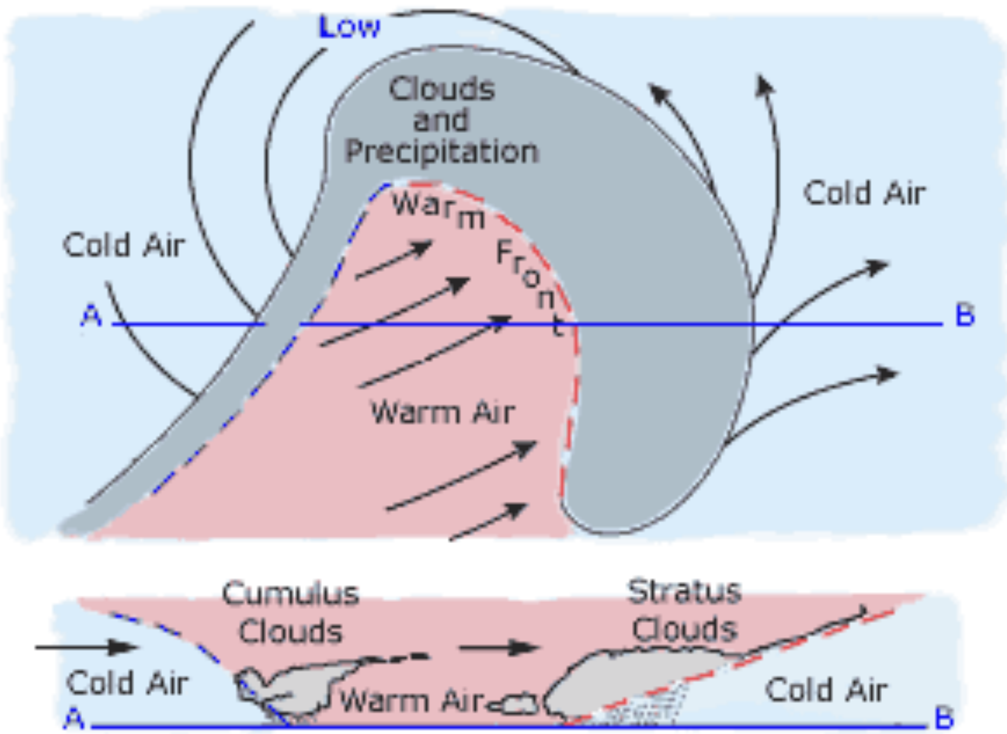
- Exponential growth of perturbations

Baroclinic Instability

- Responsible for midlatitude weather patterns
- “Cyclogenesis”

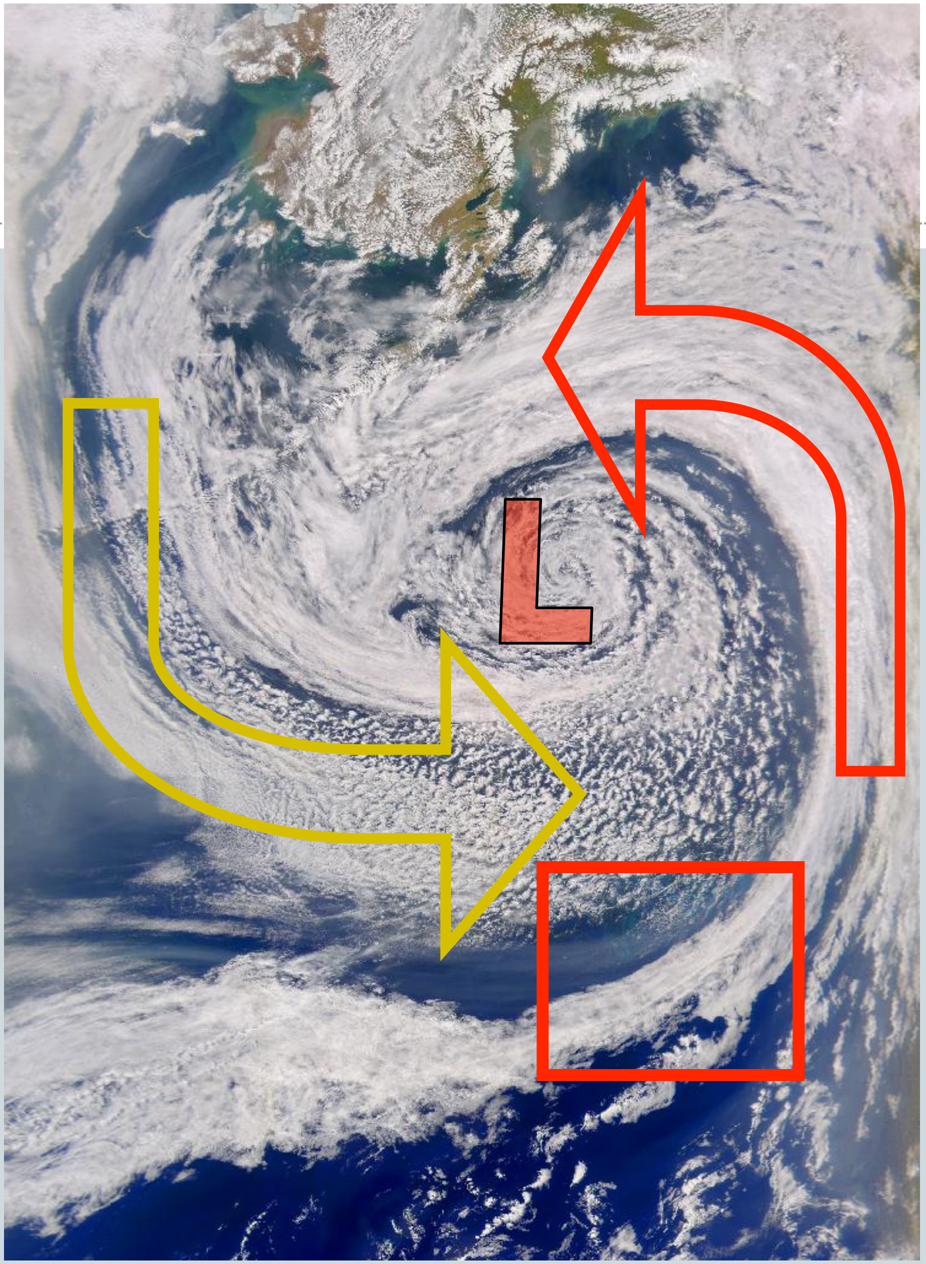


Cyclone Structure



- Center has lowest pressure
  - ~geostrophic winds.
- Warm air moves poleward
  - and upward.
  - Warm front.
- Cold air moves equatorward
  - and downward.
  - Cold front.
- Clouds & precipitation.
  - ~ "comma" shape.

Pacific Extratropical Cyclone

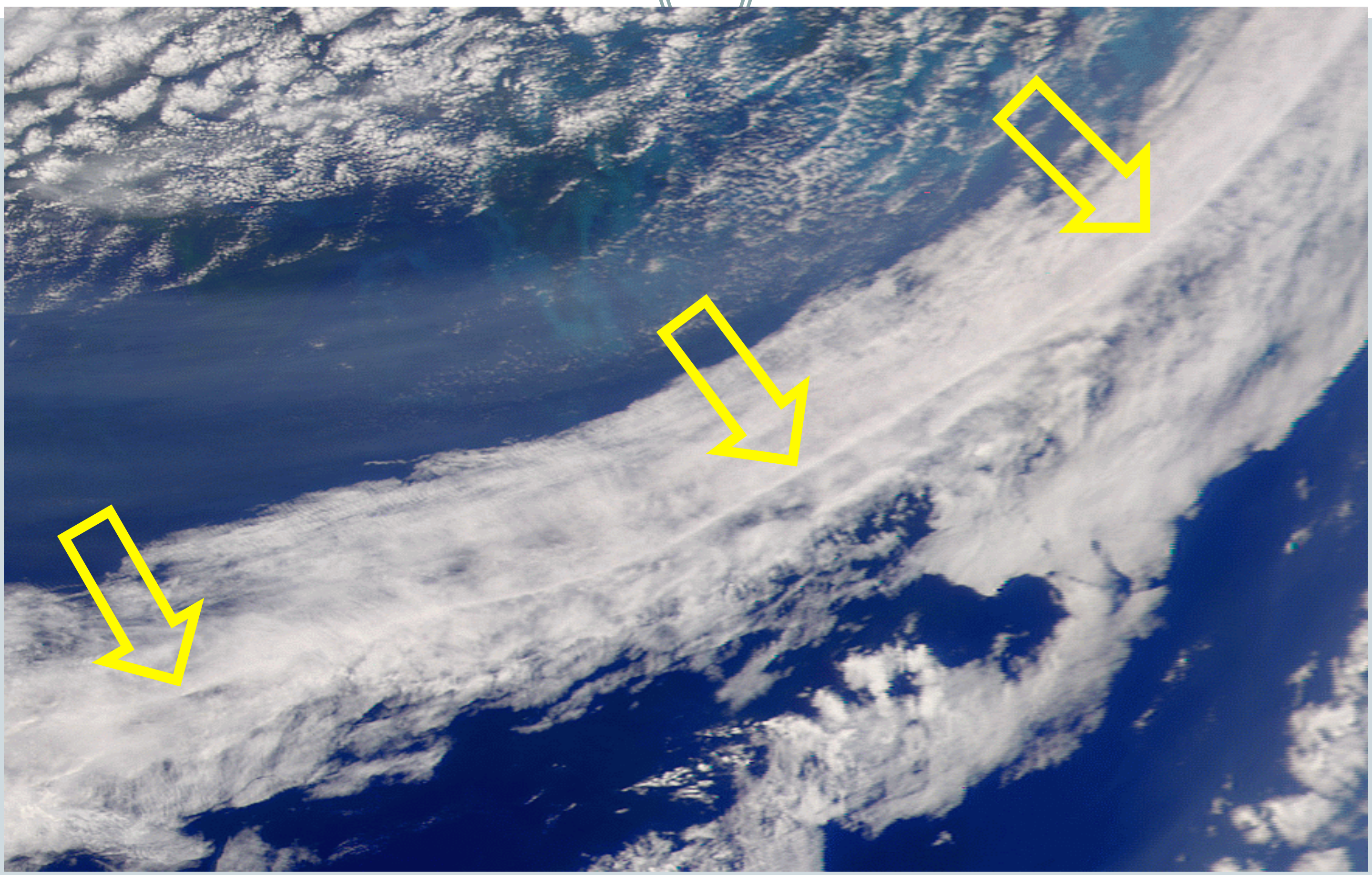


- Intense vortex
  - Cold air: shallow cellular convection
  - Warm air: stratiform cloud
- Sharp frontal boundaries

Zoom in on cold front…

Slide courtesy of Greg Hakim

Frontogenesis



Scale collapse at cold front: "rope cloud"---narrow line convection.

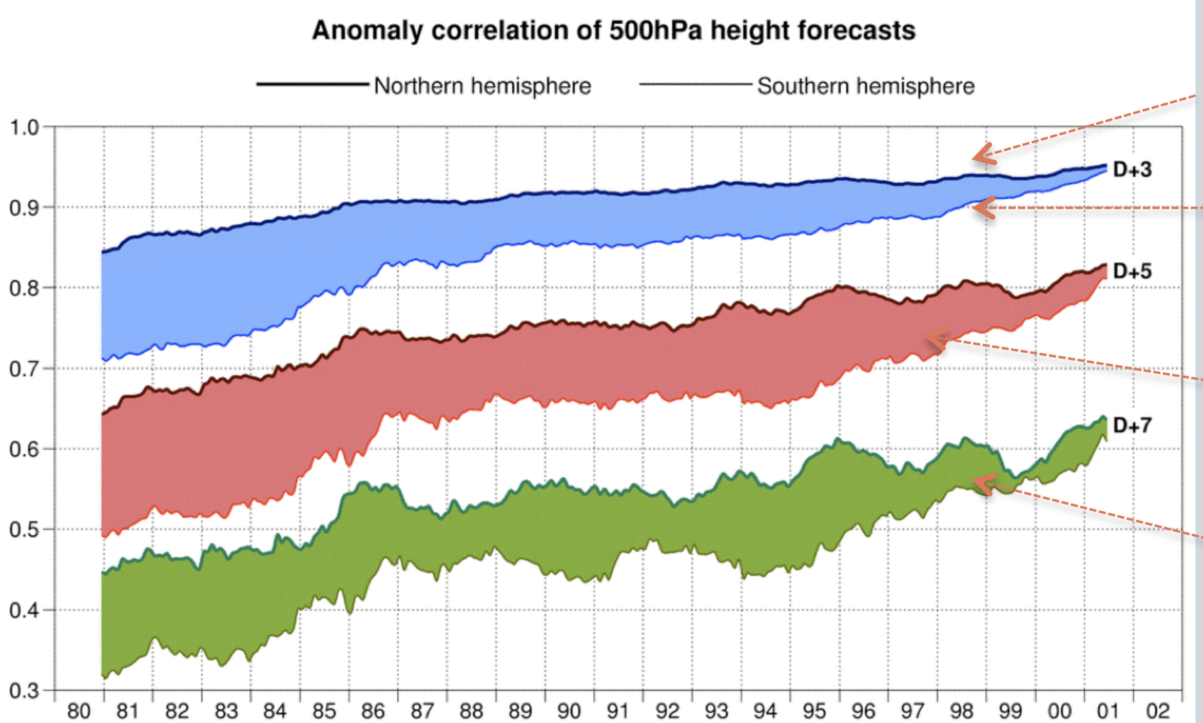
Why study "balanced models" like QG?

- We'll illustrate this with some history:
  - The first NWP experiment (Richardson, 1922)
  - The first successful NWP model (Charney, Fjortoft, & von Neumann, 1950)

All info on this topic is from Peter Lynch: Check out his book "The Emergence of NWP"!

Numerical Weather Prediction (NWP)

- Improvements in weather prediction over the last 60 years are among the most impressive accomplishments of society



Northern Hem. 3 day forecast

Southern Hem. 3 day forecast

5 day forecasts (NH & SH)

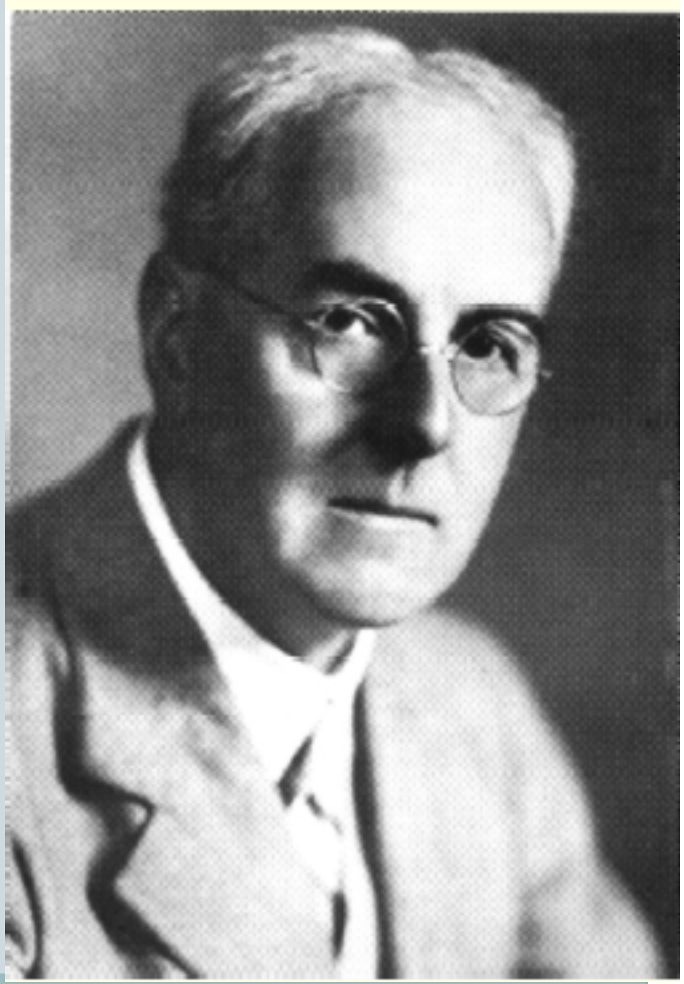
7 day forecasts (NH & SH)

1980 2002 Simmons & Hollingsworth '02

Lewis Fry Richardson

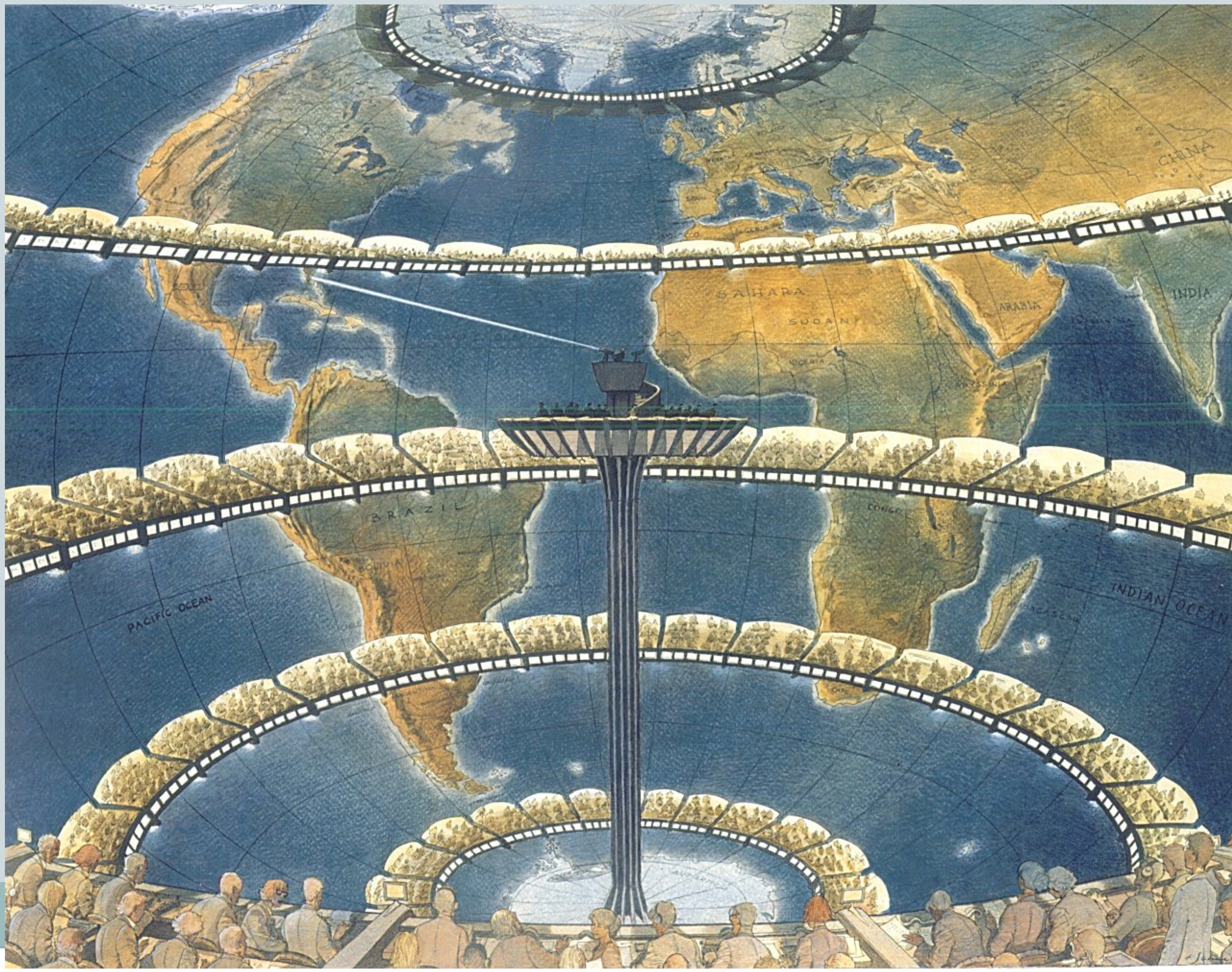
- British mathematician, physicist, atmospheric scientist
- Scientific career very influenced by his Quaker beliefs (pacifism)
- Made the first numerical weather prediction in ***1922***

Also had a dream of the future of weather prediction…



The Forecast Factory

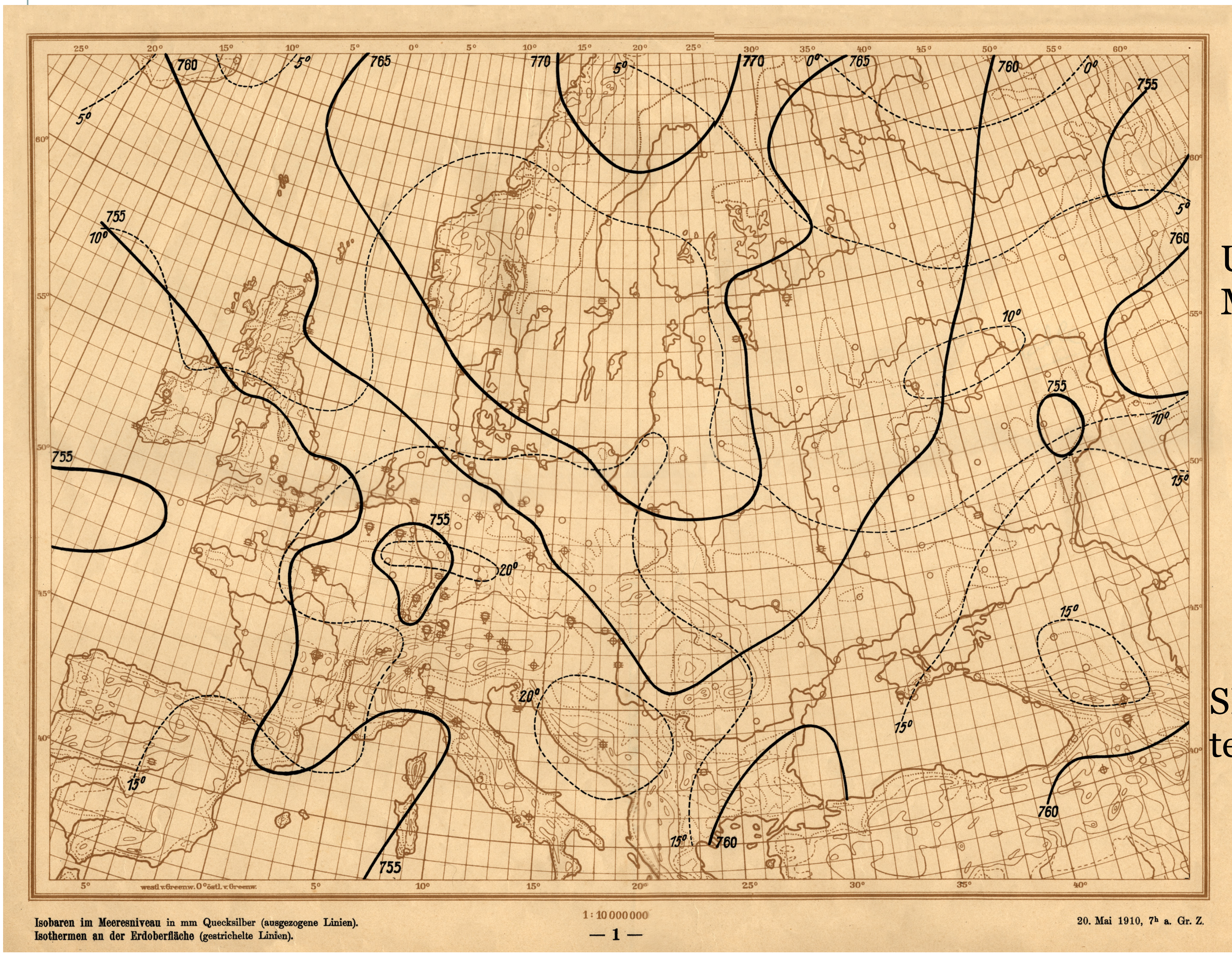
- Filled with employees ("computers") doing calculations



Richardson's dream in 1922 of a global forecasting system

He estimated 64,000 "computers" (people) would be necessary to forecast over the globe

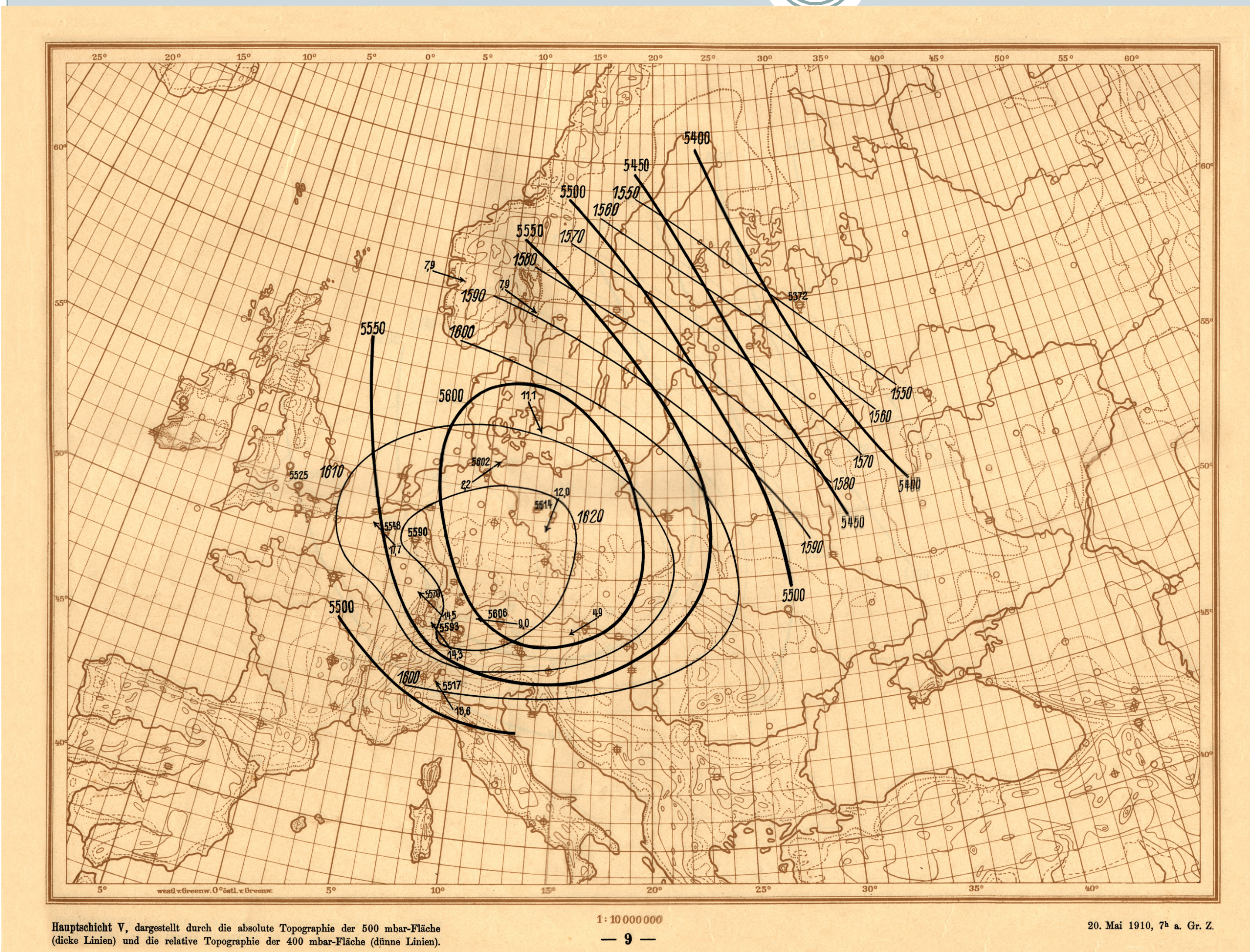
Richardson's Experiment



Used data from May 20, 1910

SLP and surface temperature

Richardson's Experiment



Data taken when Halley's Comet was passing through the atmosphere

Tabulated values from these charts by hand!

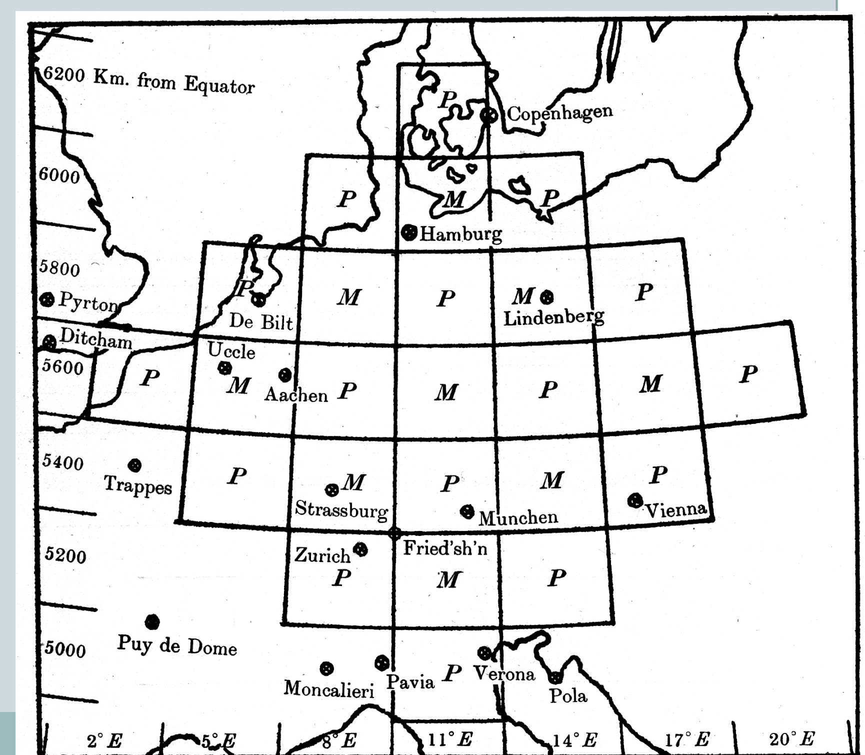
500 mbar heights and 500-400 mbar thickness

Richardson’s Calculations

- Served as ambulance driver with the Friends’ Ambulance Unit in France during WWI
  - Transported injured soldiers, often under heavy fire
- Took six weeks to perform the calculations
  - “My office was a heap of hay in a cold rest billet”
  - Peter Lynch thinks he meant 6 weeks*7 days*24 hours = 1000 hours of computation!
    - I.e., it took him the whole time he was in France, 2 years
- Calculation book was lost during the battle of Calculation book was lost during the battle of Champagne
  - But recovered months later under a heap of coal
- Eventually published in 1922

Richardson’s Calculations

- Goal: calculate the **surface pressure** tendency at one point (in Bavaria), 6 hours in the future
- Discretized into five layers in the vertical
- Used **primitive equations**
  - Assuming hydrostatic balance
- Used finite differences to calculate changes in momentum, temperature, and pressure



Richardson's *Spread-sheet*

Computing Form P xiii. Divergence of horizontal momentum-per-area. Increase of pressure

The equation is typified by: $-\frac{\partial R_{98}}{\partial t} = \frac{\partial M_{E98}}{\partial e} + \frac{\partial M_{N98}}{\partial n} - M_{N98}\frac{\tan\phi}{a} + m_{H8} - m_{H6}^{*} + \frac{2}{a}M_{H98}$. (See Ch. 4/2 #5.)

* In the equation for the lowest stratum the corresponding term $-m_{G8}$ does not appear

Longitude *11° East*, $\delta e = 441 \times 10^5$ — Latitude *5400 km North*, $\delta n = 400 \times 10^5$ — Instant *1910 May 20^d 7^h G.M.T.*, $a^{-1}.\tan\phi = 1{\cdot}78 \times 10^{-9}$ — Interval, δt *6 hours*, $a = 6{\cdot}36 \times 10^8$

Ref.:—				previous 3 columns	previous column		Form P xvi	Form P xvi	equation above	previous column	previous column	previous column
h	$\frac{\delta M_E}{\delta e}$	$\frac{\delta M_N}{\delta n}$	$-\frac{M_N \tan\phi}{a}$	$\mathrm{div}'_{EN}M$	$-g\delta t\,\mathrm{div}'_{EN}M$	Leave the subsequent columns to be filled up after the vertical velocity has been computed on Form P xvi	m_H	$\frac{2M_H}{a}$	$-\frac{\partial R}{\partial t}$	$+\frac{\partial R}{\partial t}\delta t$	$g\frac{\partial R}{\partial t}\delta t$	$\frac{\partial p}{\partial t}\delta t$
	$10^{-5}\times$	$10^{-6}\times$	$10^{-5}\times$	$10^{-5}\times$	$100\times$		$10^{-5}\times$	$10^{-6}\times$	$10^{-5}\times$		$100\times$	$100\times$
h_0							0					0
	−61	−245	−6	−312	656				−229	49·5	483	
h_2							−83					483
	367	−257	2	112	−236			0·06	−136	29·4	287	
h_4							165					770
	93	−303	−16	−226	478			0·11	−124	26·8	262	
h_6							63					1032
	32	−55	−12	−35	74			0·07	−110	23·8	233	
h_8							138					1265
	−256	38	−8	−226	479			0·03	−88	19·0	186	
h_G												1451
Note: $\mathrm{div}'_{EN}M$ is a contraction for $\frac{\delta M_E}{\delta e} + \frac{\delta M_N}{\delta n} - M_N\frac{\tan\phi}{a}$					SUM = 1451 $= \frac{\partial p_G}{\partial t}\delta t$							check by $\Sigma - g\delta t\,\mathrm{div}'_{EN}M$

Richardson's Computing Form P_{XIII}

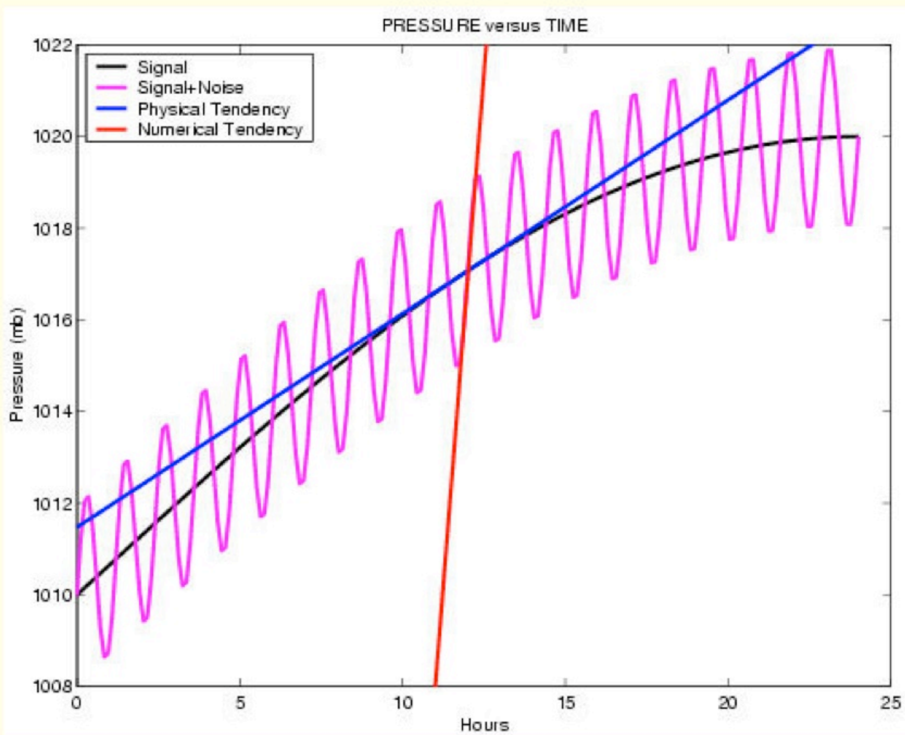
The figure in the bottom right corner is the forecast change in surface pressure: 145 mb in six hours!

Richardson's Forecast Bust

- Why such a failure?
- Not due to bad numerics, as many claim
  - He only took one time step, so numerical instabilities can't develop
- Rather it has to do with unbalanced motions

Extrapolating noisy rates of change

Tendency of a Noisy Signal



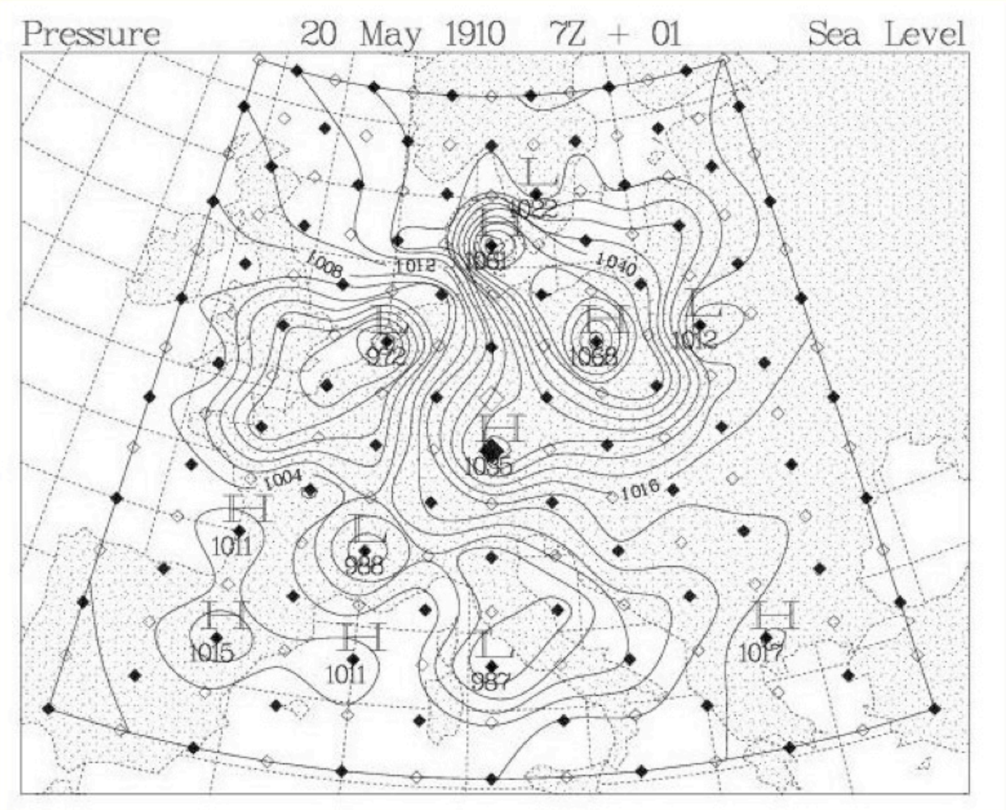
Unbalanced motions which average to zero on top of a smoothly changing signal can really mess up forecasts!

Balancing initial conditions is still a problem today!
(big problem in data assimilation)

A simple schematic illustrating how extrapolating a noisy signal is dangerous…

Richardson's forecast

Forecast without Filtering



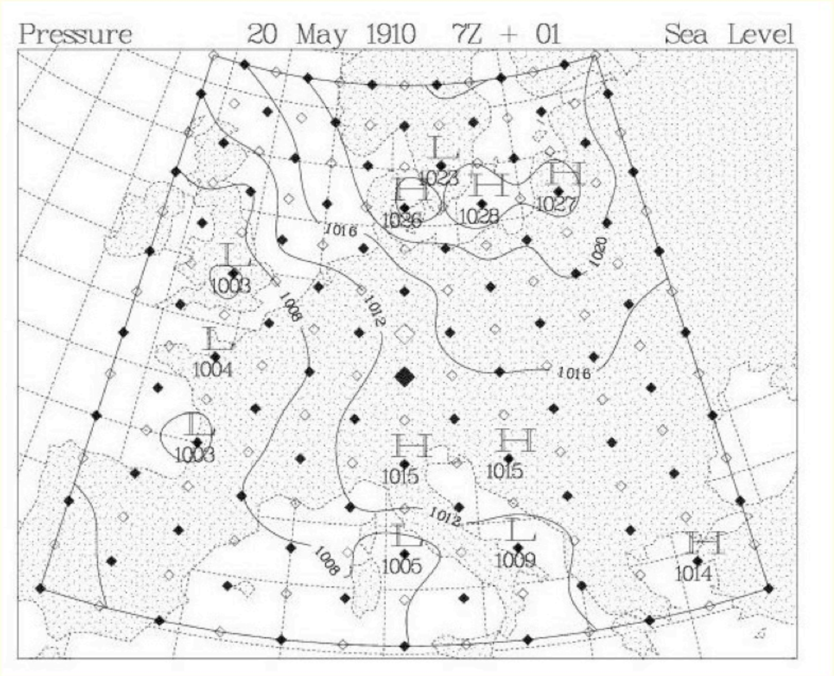
Short-range forecast of sea-level pressure, from *uninitialized data.* The contour interval is 4 hPa. Single forward time step of size $\Delta t = 3600\,\mathrm{s}$.

Richardson’s Forecast

- Richardson himself realized that gravity waves (“imbalanced initial conditions”) were the problem
- He suggested smoothing of initial conditions
  - And proposed 5 different methods for this
- Unfortunately he couldn’t implement them due to computational expense
  - But we can reproduce the results using today’s computers…

"Balancing" the initial conditions

Forecast with Filtering



Short-range forecast of sea-level pressure, from *filtered data*. The contour interval is 4 hPa. Single forward time step of size $\Delta t = 3600\,\mathrm{s}$.

The First Successful NWP Experiment

- Fast gravity waves were the problem:
  - Why not try predicting with a model that has no gravity waves?
- John von Neumann, Jule Charney, Ragnar Fjortoft
- Research proposal proposed three uses for NWP:
  - Weather prediction (duh)
  - Planning where to take observations
  - Weather modification!

ENIAC Forecast Grid

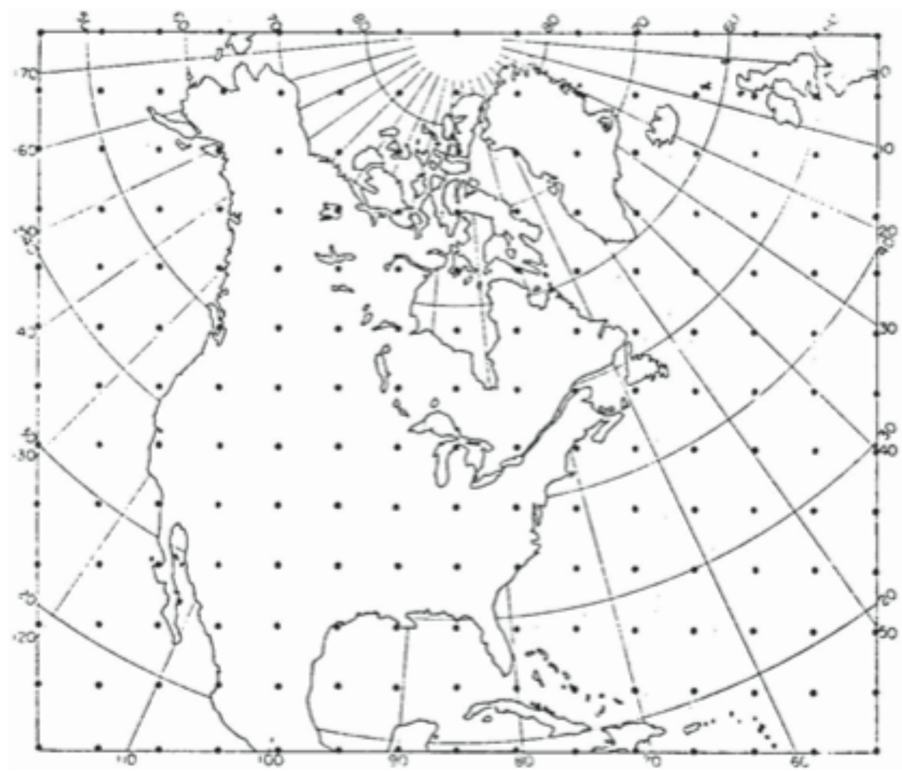


FIG. 2. Computation grid used for the ENIAC forecasts. One line is omitted from the southern edge and two lines from the remaining edges (from CFvN).

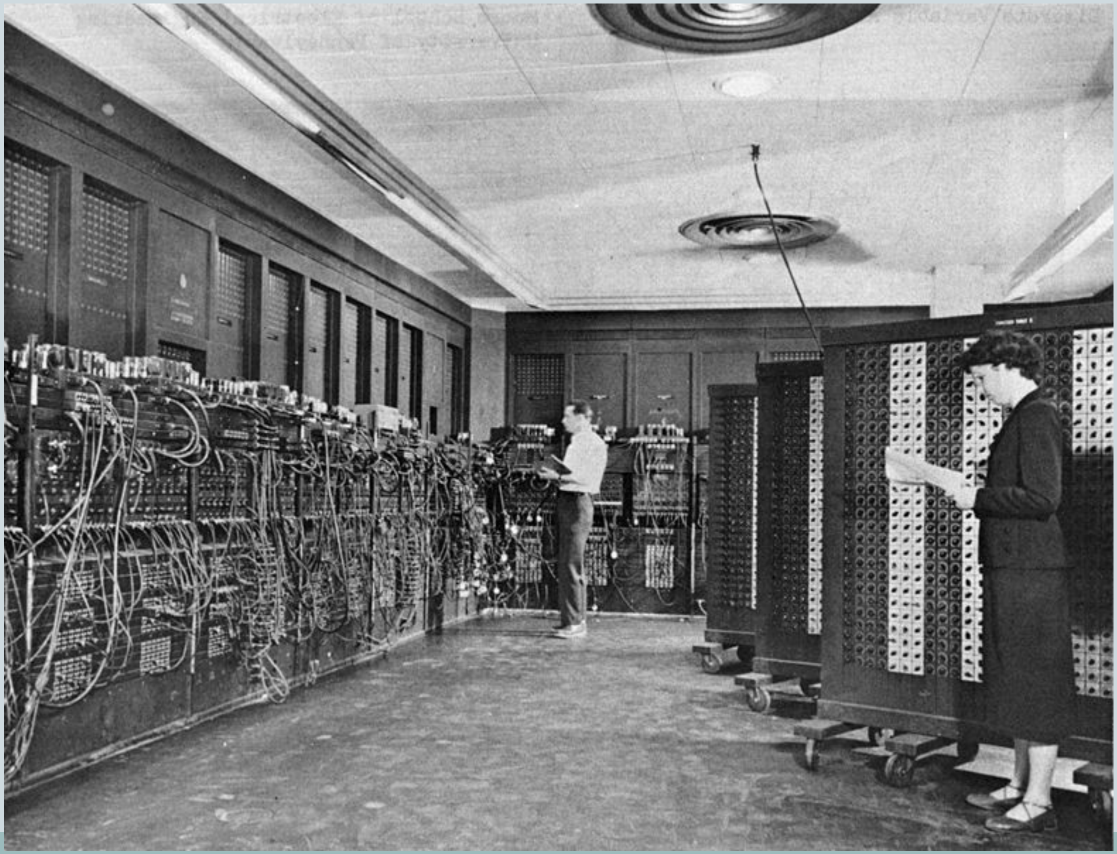
Used barotropic model (no gravity waves, no problems with imbalanced initial conditions)

Same model we'll use in class to study Rossby waves

We'll also use the barotropic model in lab to make some weather forecasts with modern data!

The First Computer!

- ENIAC: The Electronic Numerical Integrator and Computer



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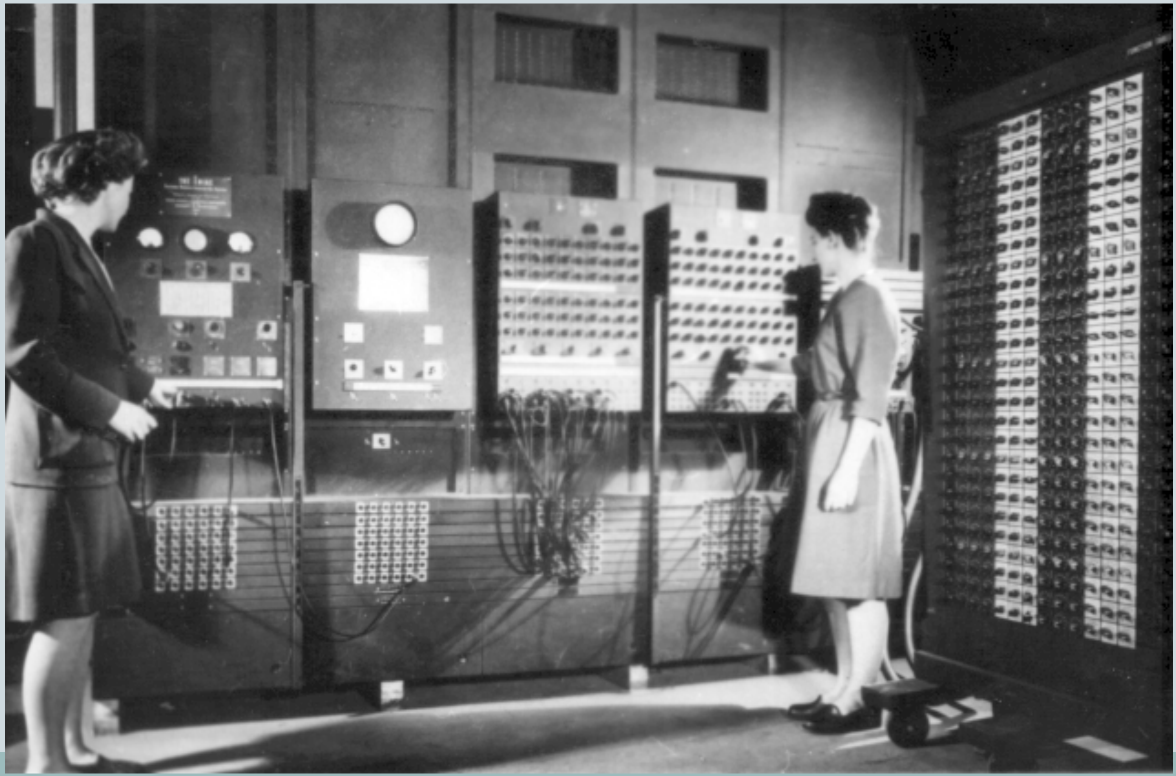


First Forecast

Initial conditions

Observed height 24 hrs later

Observed and computed change in height

Forecast height 24 hrs later

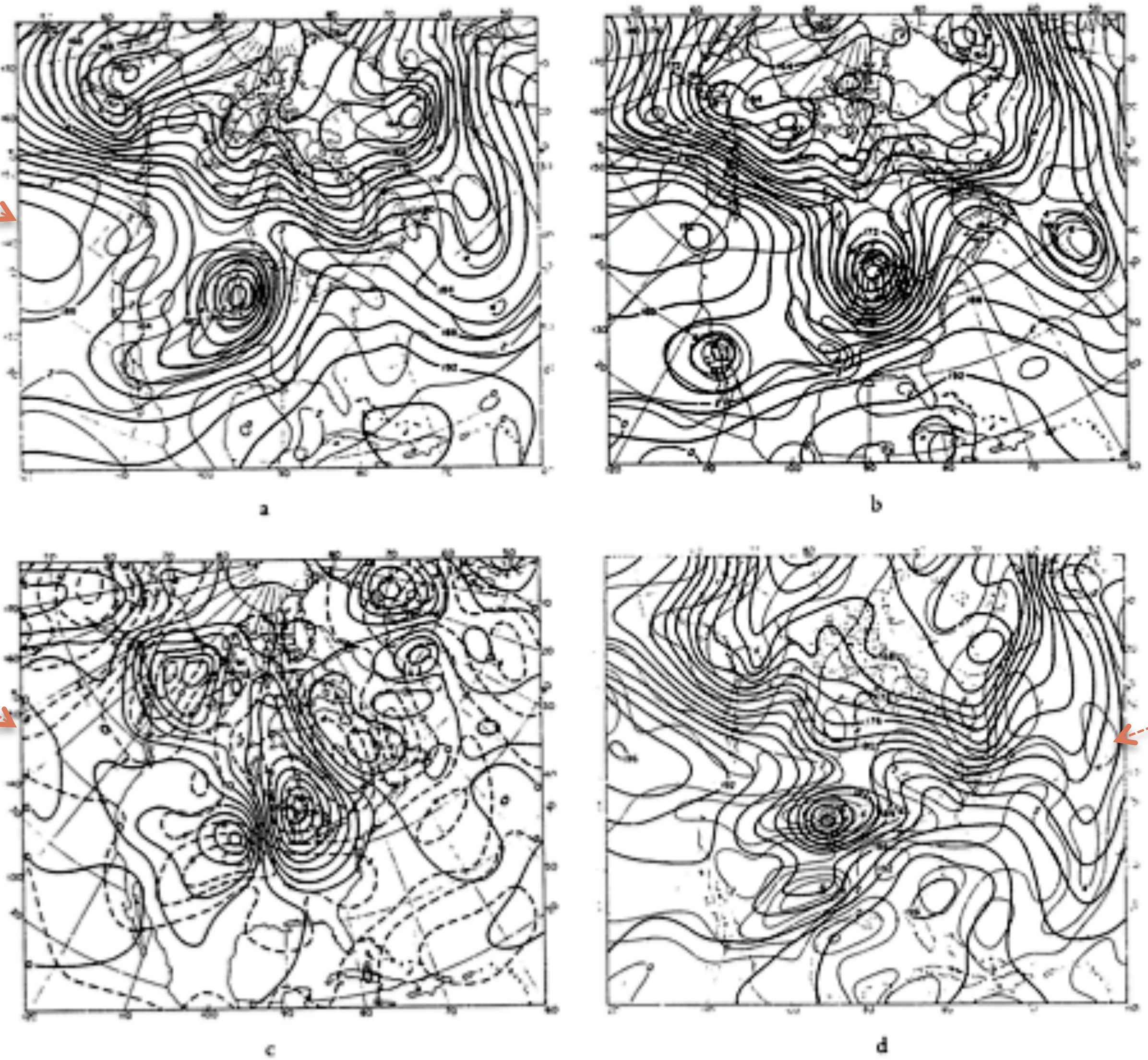
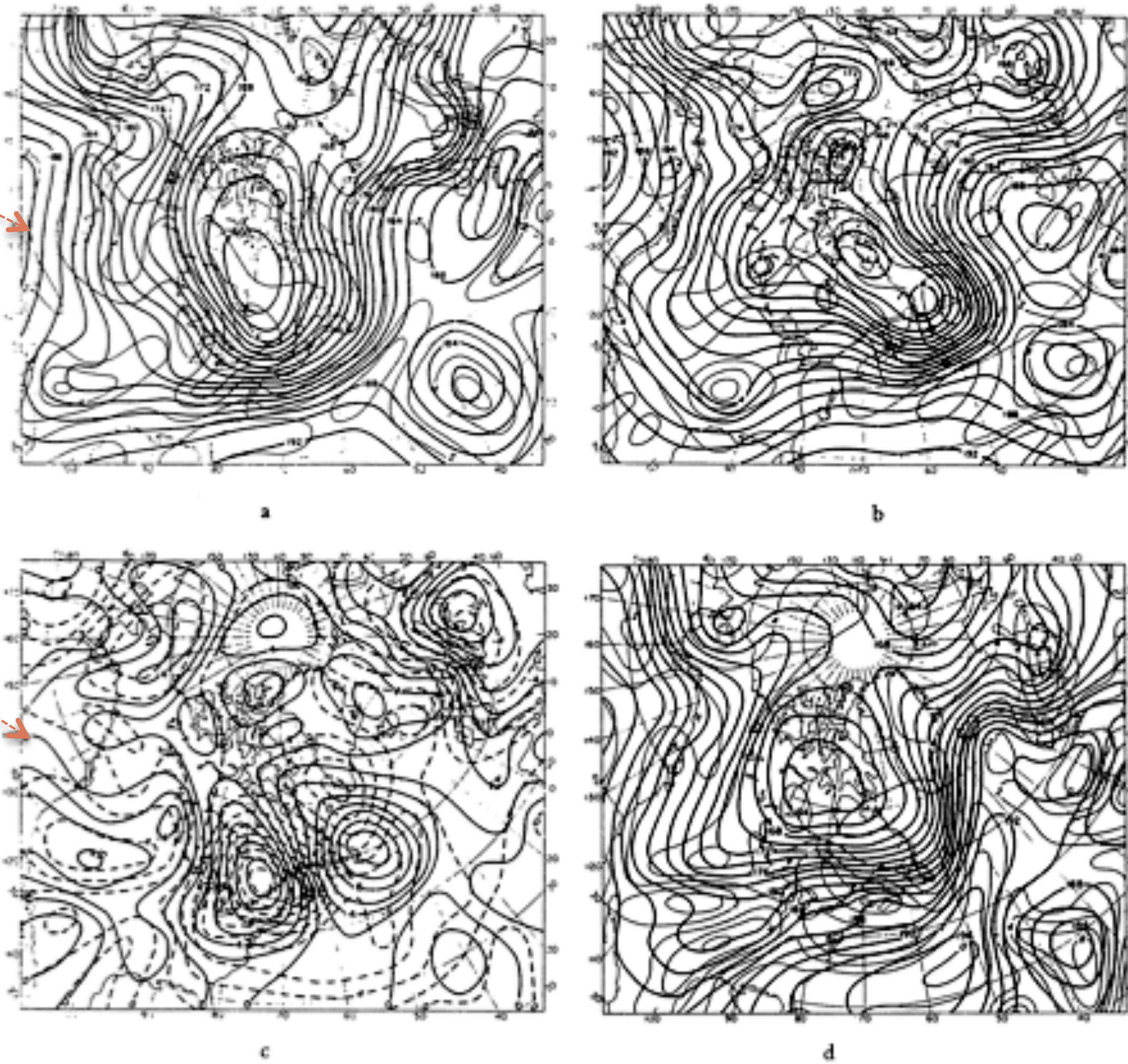


Fig. 2. Forecast of January 5, 1949, 0300 GMT: (a) observed z and η at $t = 0$; (b) observed z and η at $t = 24$ hours; (c) observed (continuous lines) and computed (broken lines) 24-hour height change; (d) computed z and η at $t = 24$ hours. The height unit is 100 ft and the unit of vorticity is $1/3 \times 10^{-4}$ sec^{-1}.

Second Forecast

Initial conditions

Observed height 24 hrs later



Observed and computed change in height

Forecast height 24 hrs later

Fig. 3. Forecast of January 30, 1949, 0300 GMT. (See Fig. 2 for explanation of diagrams.)

Third Forecast

Initial conditions

Observed height 24 hrs later

Observed and computed change in height

Forecast height 24 hrs later

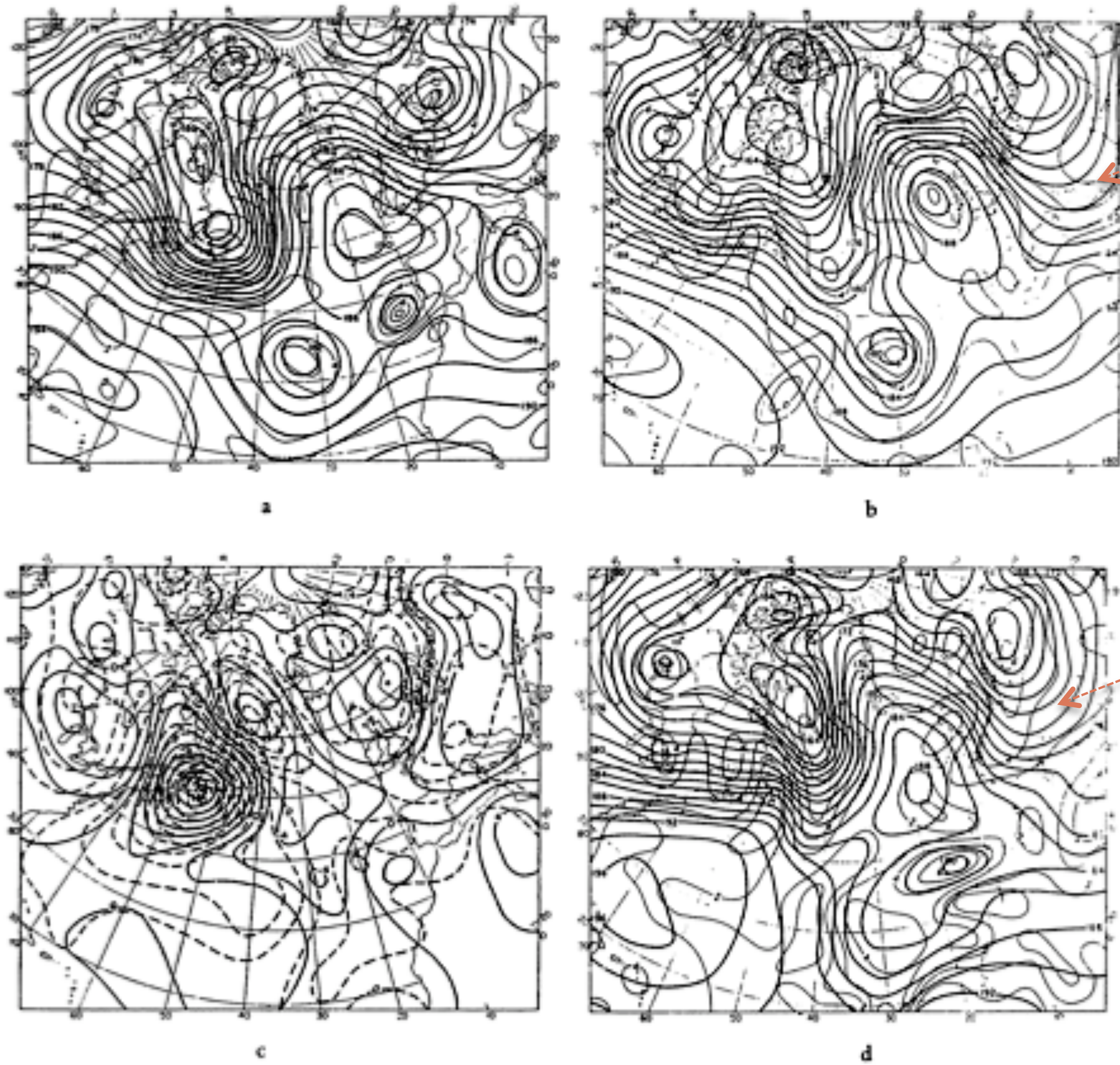


Fig. 4. Forecast of January 31, 1949, 0300 GMT. (See Fig. 2 for explanation of diagrams.)

Fourth Forecast

Initial conditions

Observed height 24 hrs later

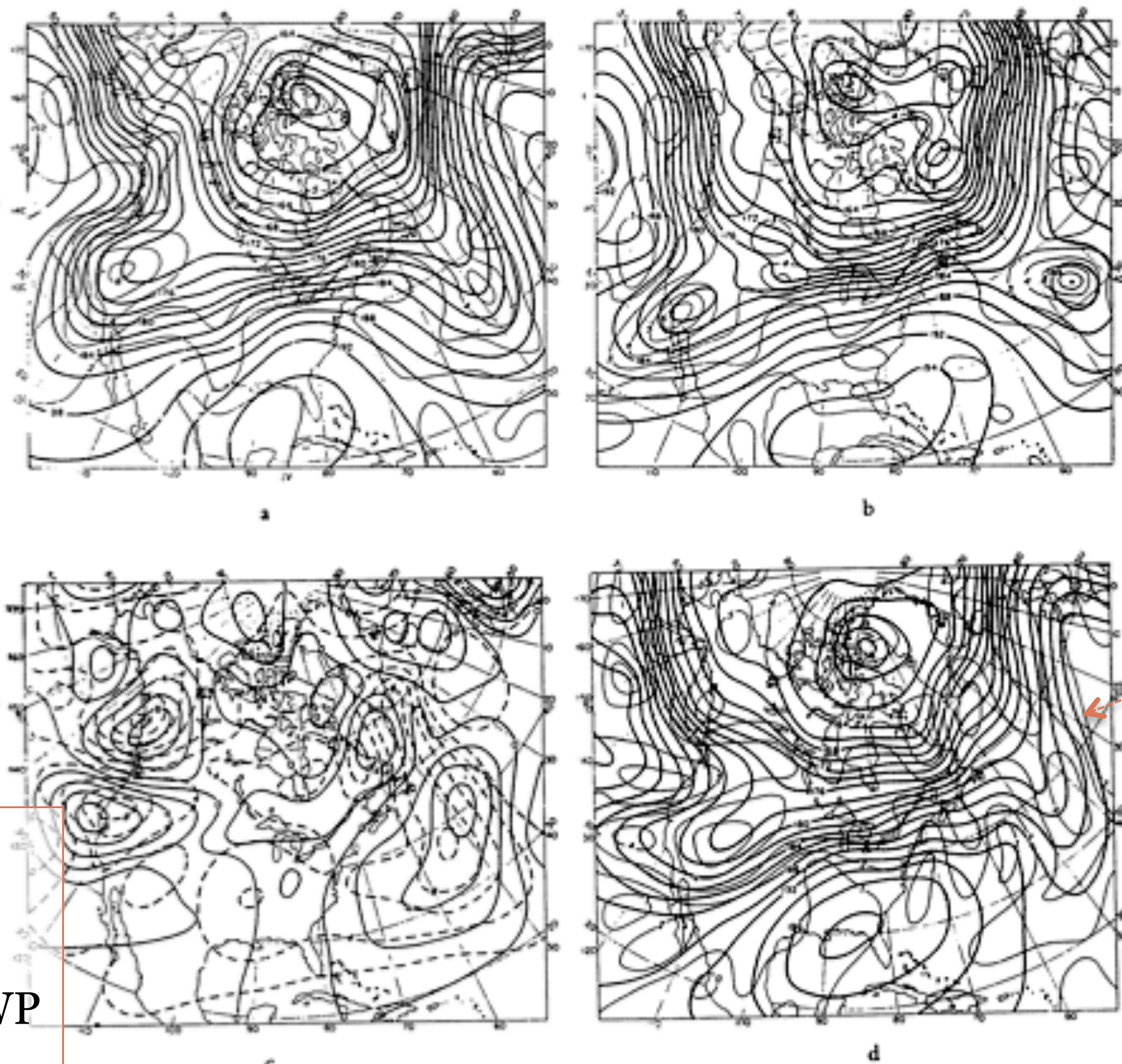


Fig. 5. Forecast of February 13, 1949, 0300 GMT. (See Fig. 2 for explanation of diagrams.)

Observed and computed change in height

Forecast height 24 hrs later

Results are not that impressive for first "successful" NWP forecast!

First Operational NWP Systems

- NWP really took off though & quickly improved!
- December 1954: Royal Swedish Air Force Weather Service in Stockholm
  - Model developed at the Institute of Meteorology at the University of Stockholm (Rossby, etc)
  - Barotropic model, 3 forecasts per week of North Atlantic
- May 1955: Joint Numerical Weather Prediction Unit, Maryland
  - 3 level QG model
- 1966: US uses 3-level primitive equation model
- Global coverage since 1973