Vilhelm Bjerknes Medal Lecture
EGU General Assembly, 25 April 2012

Vilhelm Bjerknes's "First task of theoretical meteorology":

Assimilation of observational data for atmospheric monitoring and forecasting

Adrian Simmons

European Centre for Medium-Range Weather Forecasts

ECMWF

Our starting point

Vilhelm Bjerknes's 1904 paper:

> "Das Problem der Wettervorhersage, betrachtet vom Standpunkte der Mechanik und der Physik"

enunciated the basic principles of numerical weather prediction

identifying tasks for observational and theoretical meteorology:

- to determine the initial state of the atmosphere
- to determine the evolution from one state to another

The first task of theoretical meteorology

“Based on the observations made, the first task of theoretical meteorology will then be to derive the clearest possible picture of the physical and dynamical state of the atmosphere at the time of the observations. […] From the directly observable quantities we must calculate as comprehensively as possible all accessible data on the non-observable ones. For that purpose one has to utilize the relationships between the different quantities. Thus […] one must extensively use dynamical-physical methods”

Translated from the original German by Esther Volken and Stefan Brönnimann

The second task …

"The second and *paramount* task of theoretical meteorology will be to construct the pictures of the future states of the atmosphere from the picture of the current state of the atmosphere as a starting point, either according to the method outlined here, or according to a method of a similar kind."

"paramount " is a translation of "*höchste*"

Published alternatives are *"most important"* and *"most challenging"*

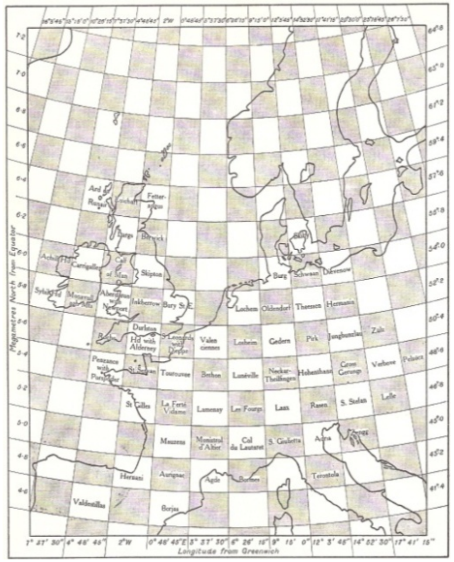
Modified from the translation of Volken and Brönnimann

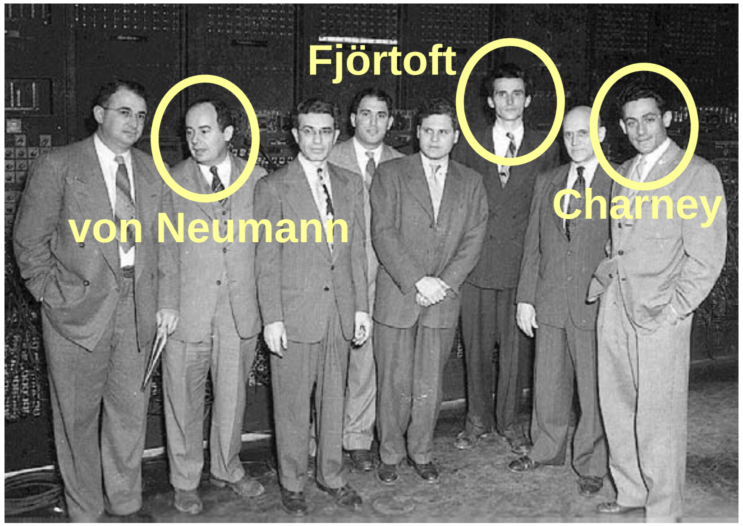
Next steps

The details set out in L.F Richardson's 1922 book:

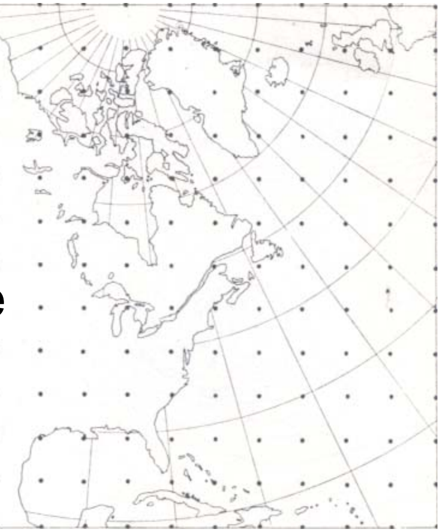
WEATHER PREDICTION
BY NUMERICAL PROCESS

"The scheme is complicated because the atmosphere is complicated"

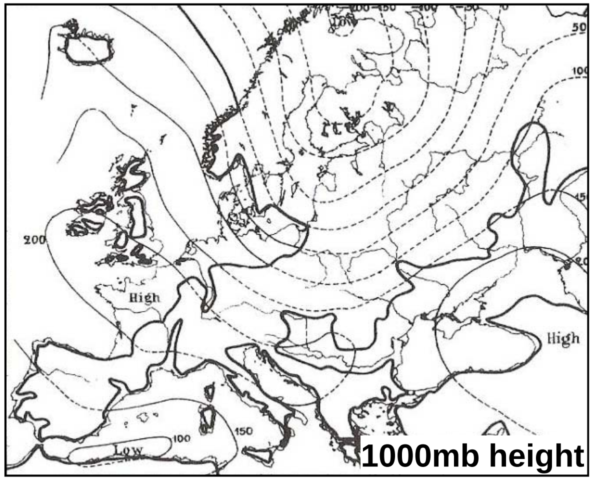


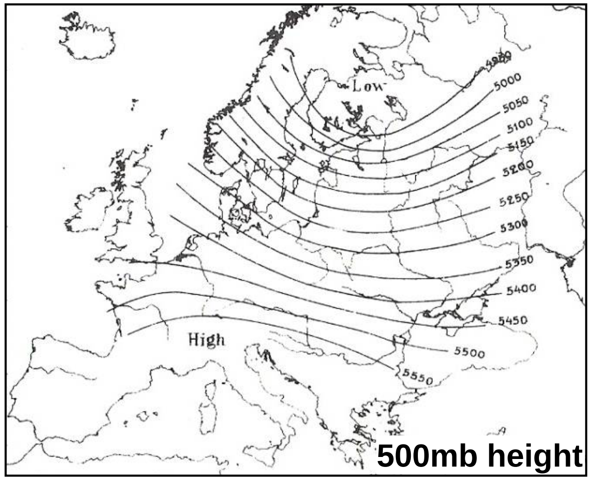


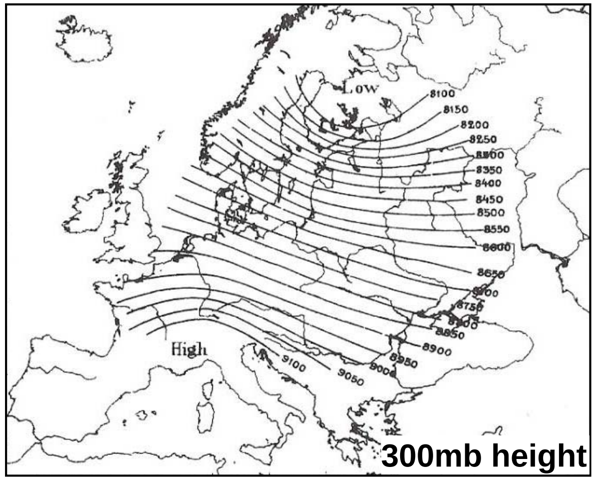
In 1950, Charney, Fjörtoft, von Neumann and colleagues make first numerical forecast, exploiting the advent of the electronic computer and rational approximation of the governing equations



Bjerknes and Sandström (1910): pioneering the isobaric weather map

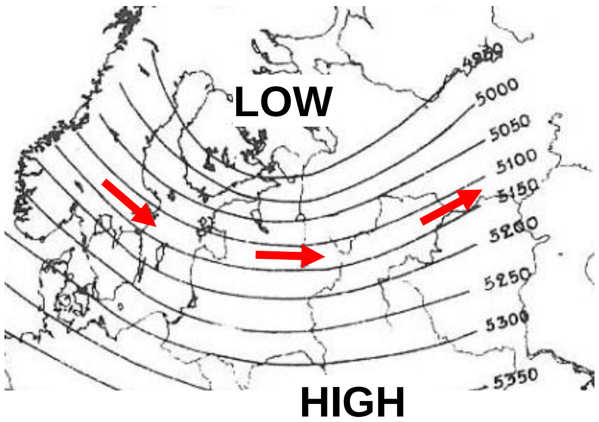






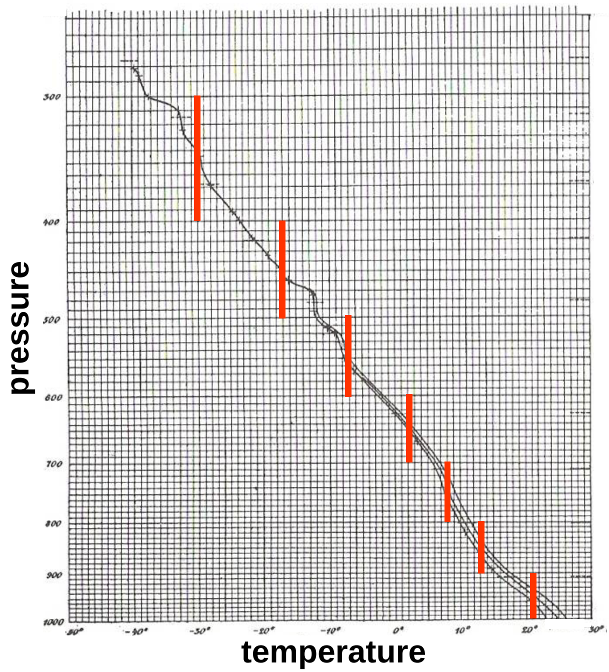
$$\phi = gz = R\int_{p}^{p_s} T\,d(\ln p)$$

built up as sum of layer-averaged temperatures



$$fv = \frac{\partial \phi}{\partial n}$$

geostrophic wind inversely proportional to distance between contours



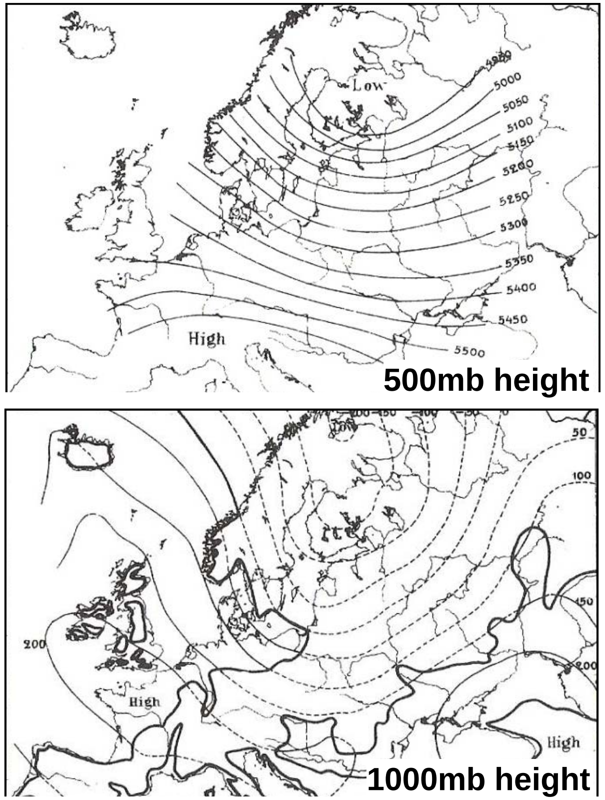
Numerical Integration of the Barotropic Vorticity Equation

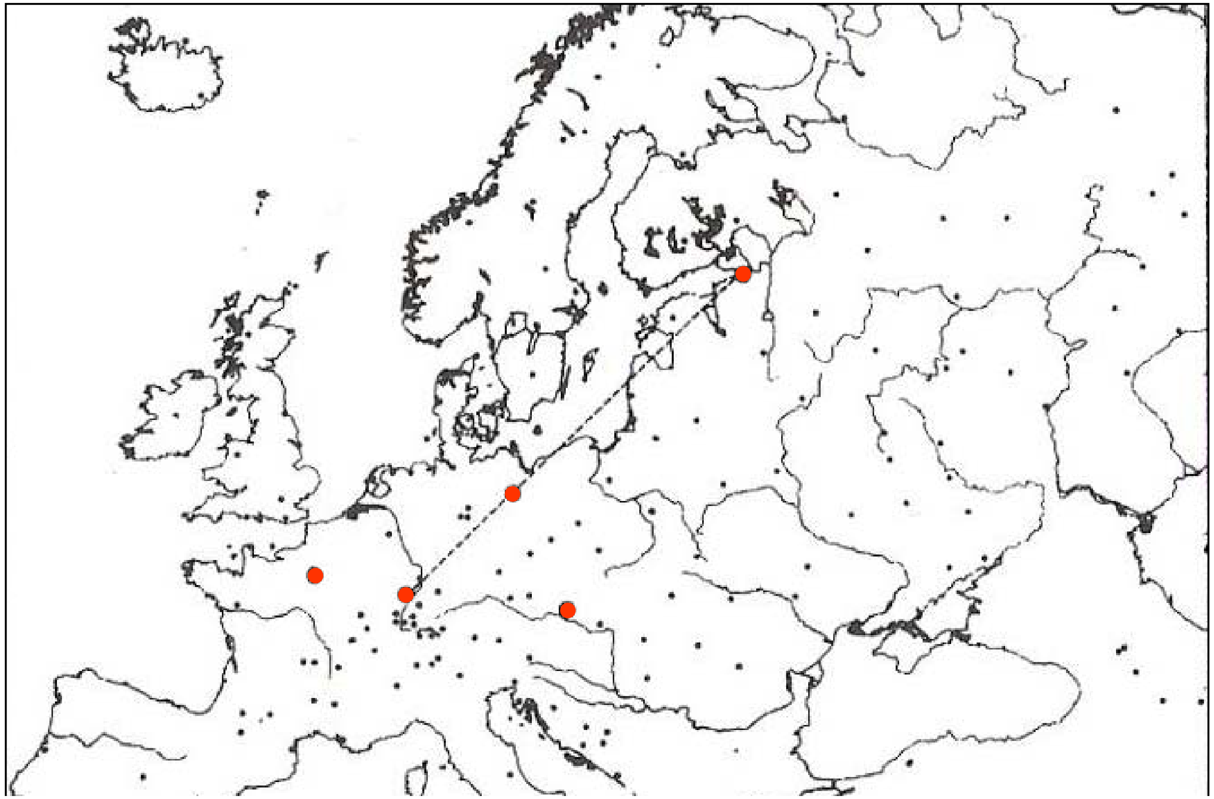
By J. G. CHARNEY, R. FJÖRTOFT[1], J. von NEUMANN

The data were taken from the conventional 500 mb analyses of the U. S. Weather Bureau and were accepted without modification in interpolating for the initial values of z at the grid points. It was realized that the conventional analyst pays more attention to wind direction than to wind speed and more attention to directional smoothness of the height contours than to their spacing, but it was thought that the more or less random errors introduced in this way would be smoothed out in the integration. Unhappily this was not always so, and it now appears that an objective analysis would have been preferable.

1950: Tellus, 2, 237-254

Bjerknes and Sandström (1910): Observational coverage for 7 November 1901





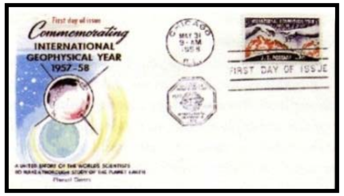
On November 7, 1901, in the morning and forenoon there ascended* from Paris one registering balloon with two instruments; from Strassburg two registering and one manned balloon; from Berlin two registering and one manned balloon; from Vienna one registering and two manned balloons. From St. Petersburg one registering balloon ascended on the following morning, November 8. This ascent has been treated as simultaneous with the others, our aim being only to exemplify the

Development of the observing system

1940s: Establishment of network of radiosonde measurements from balloons launched from North Atlantic and Pacific Weather Ships

Ship Alpha

1957: Radiosonde network enhanced in southern hemisphere for the InternationalGeophysical Year



1972: Operational sounding of temperature and humidity from polar-orbiting satellite
Some data from commercial aircraft

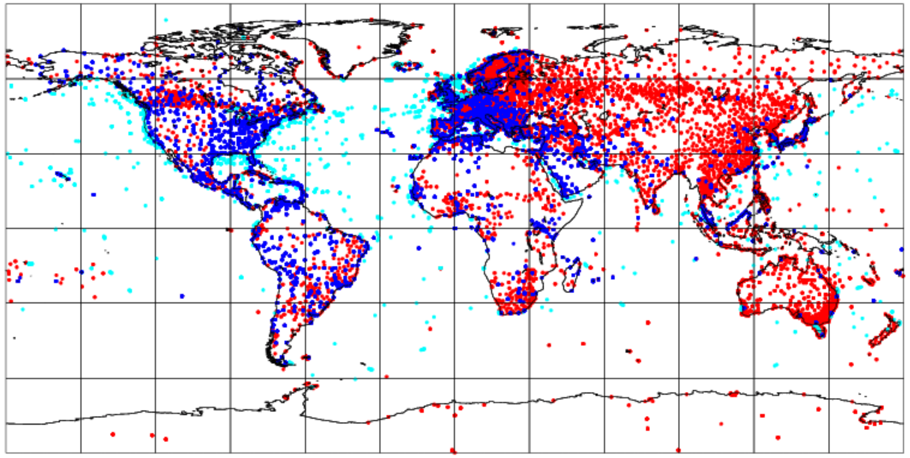
NOAA-2
15 Oct 1972

1979: Improved sounding from polar orbiters
Winds from geostationary orbit
Much more data from commercial aircraft
Drifting buoys

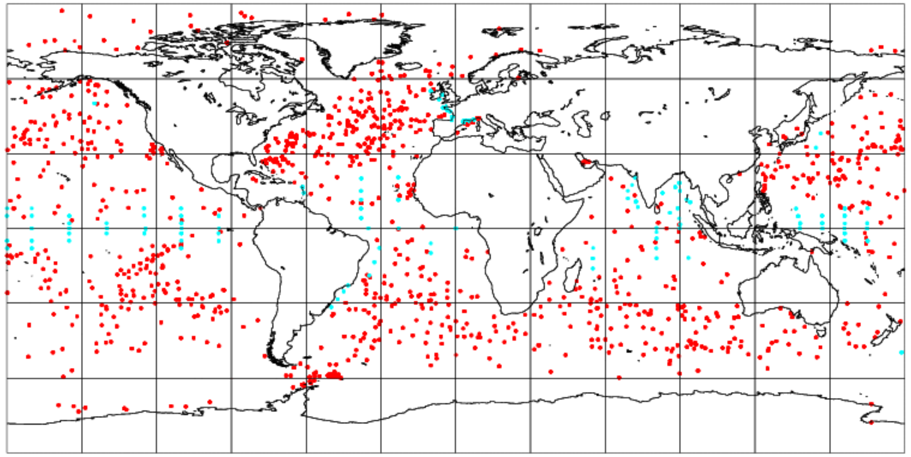
Observational data received by ECMWF 09-15UTC 9 April 2012

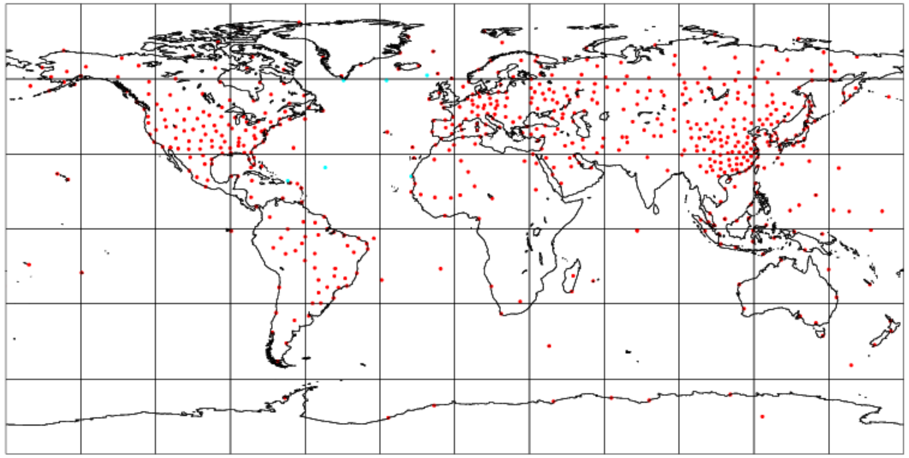
Near-surface observations

Land stations and ships

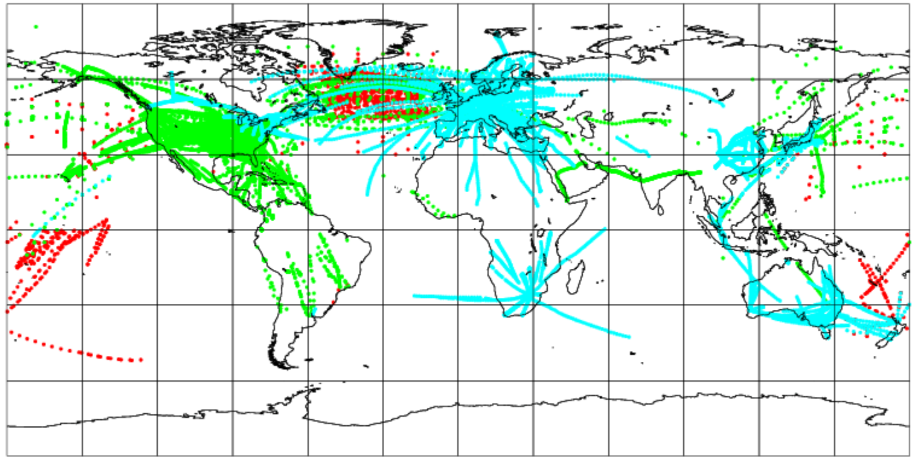


Drifting and fixed buoys





Balloon-borne radiosondes



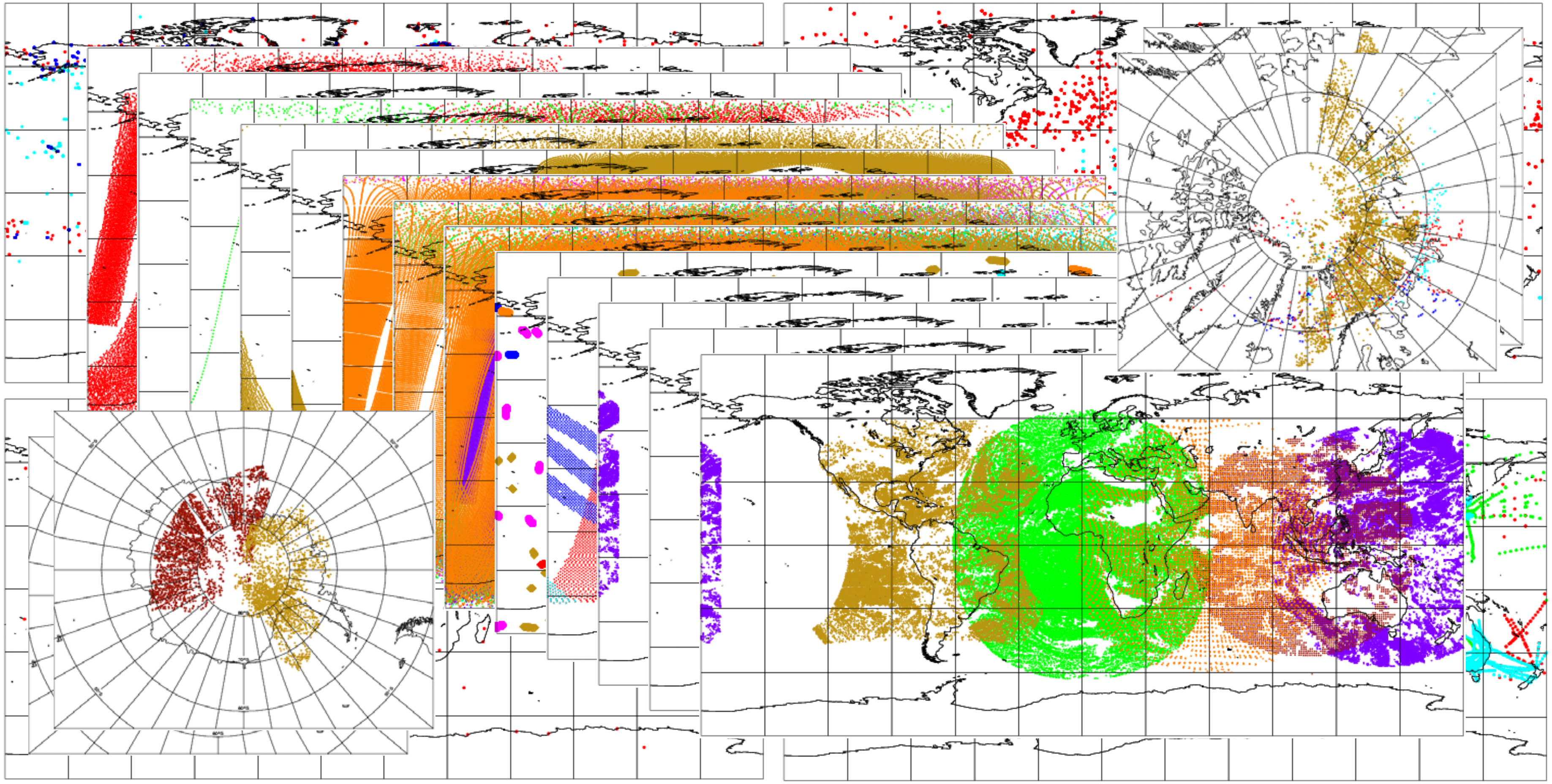
Commercial aircraft

Upper-air observations

Observational data received by ECMWF
09-15UTC 9 April 2012

Near-surface observations

Land stations and ships **Drifting and fixed buoys**

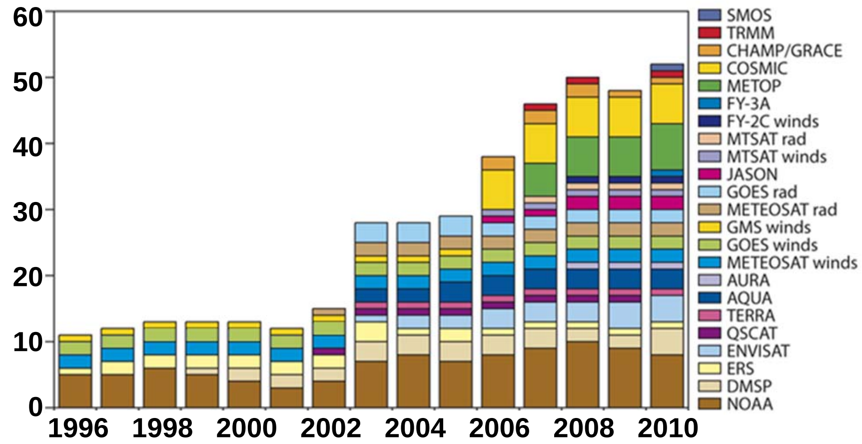


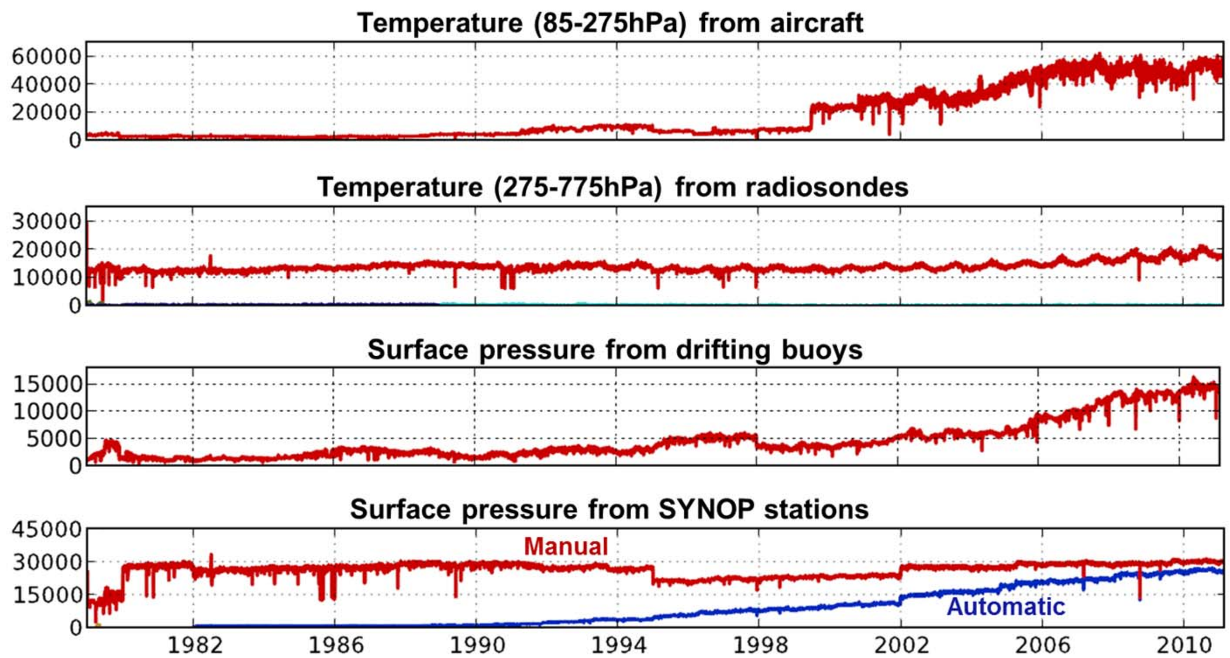
Balloon-borne radiosondes **Commercial aircraft**

Upper-air observations

Increases in observational types and numbers

Number of satellite-borne instruments from which data were assimilated routinely by ECMWF from 1996 to 2010



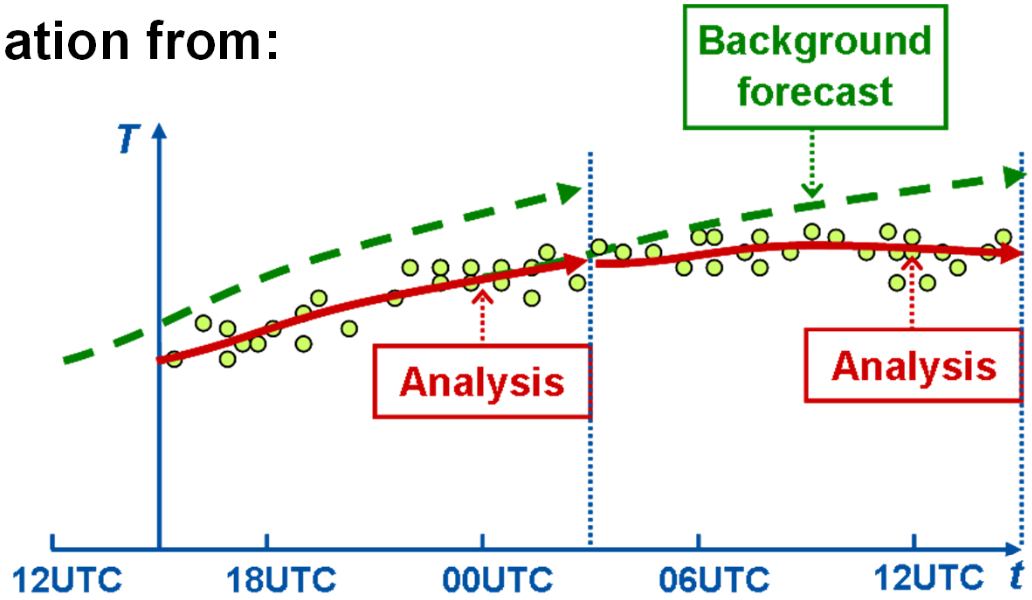


Examples of daily counts of *in situ* data used in ERA-Interim from 1979 to 2011

Data assimilation: combining the first and second tasks of theoretical meteorology

Data assimilation blends information from:

- observations
- a short "background" model forecast
- estimates of observational and background errors
- dynamical relationships built into the representation of background errors



4D variational assimilation as used in ERA-Interim

to produce an estimate of the atmospheric state

Model carries information from earlier observations forward in time and spreads it in space

Information is spread from one variable to another by the model and by background-error relationships

But the second task remained paramount for some time

Data assimilation was

- proposed by Gilchrist and Cressman (1954) and Smagorinsky, and first demonstrated by Bergthórsson and Döös (1955)

Emphasis continued to be placed largely on model development

- though global forecasting became operational in the USA in 1974

ECMWF was conceived around 1970 as the EMCC

- the European Meteorological Computing Centre
- concentrating on running the forecast model
- importing the global analysis from another institution

Good sense prevailed, but when ECMWF started operations in 1979

- its modellers outnumbered data assimilation personnel by 2:1
- a single 10-day global forecast dominated daily operational computer usage
- data assimilation was generally “a minor and often neglected sub-discipline of numerical weather prediction” (Daley, 1996)

ECMWF systems for operational forecasting and monitoring through reanalysis

Operations (1979 - present)

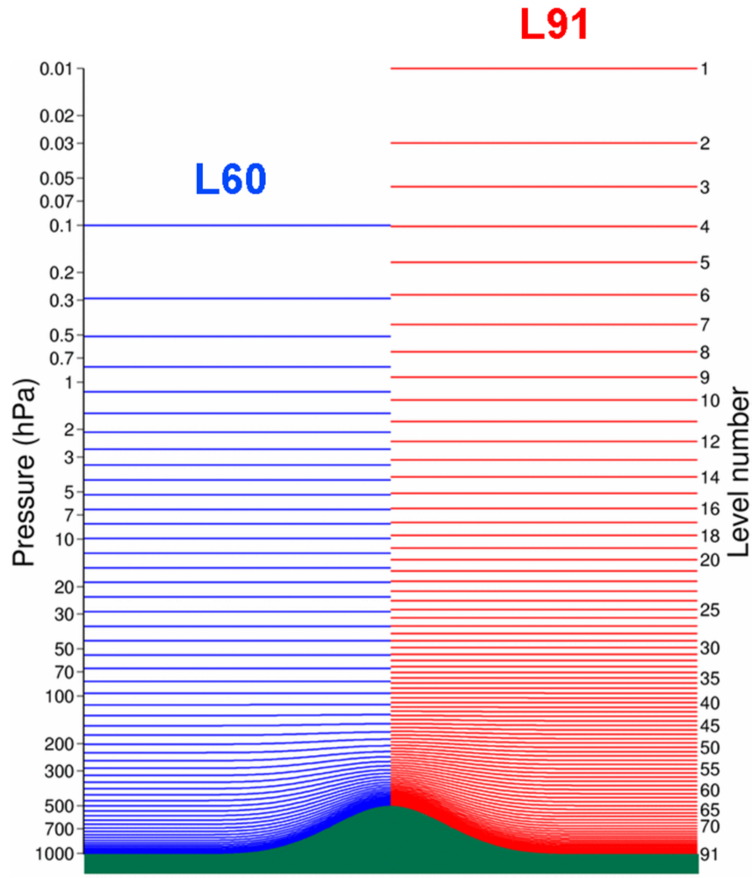
- 210 to 16 km horizontal resolution
- 15 to 91 levels (2 - 39 above 100hPa)
- many changes to the model and the way observational data are assimilated

ERA-40 reanalysis (1958 - 2001)

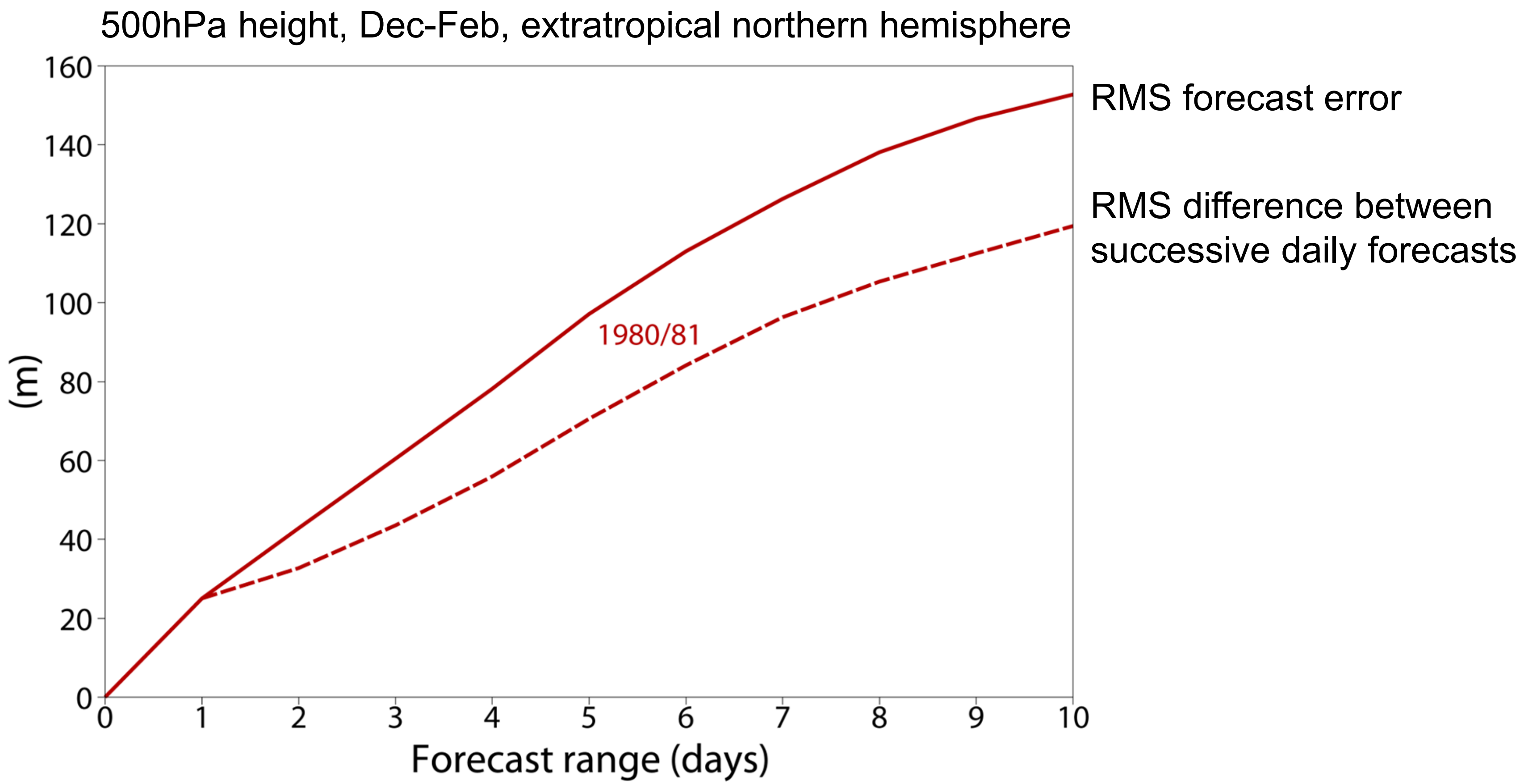
- 125 km horizontal resolution
- 60 levels, 25 above 100hPa
- fixed 2001 version of forecasting system
- 6h 3D-Var (space variational) assimilation

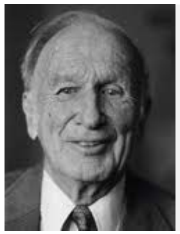
ERA-Interim reanalysis (1979 - …)

- 80 km horizontal resolution
- 60 levels, 25 above 100hPa
- fixed 2006 version of forecasting system
- 4D-Var (space-time variational) assimilation, with 12-hourly cycling



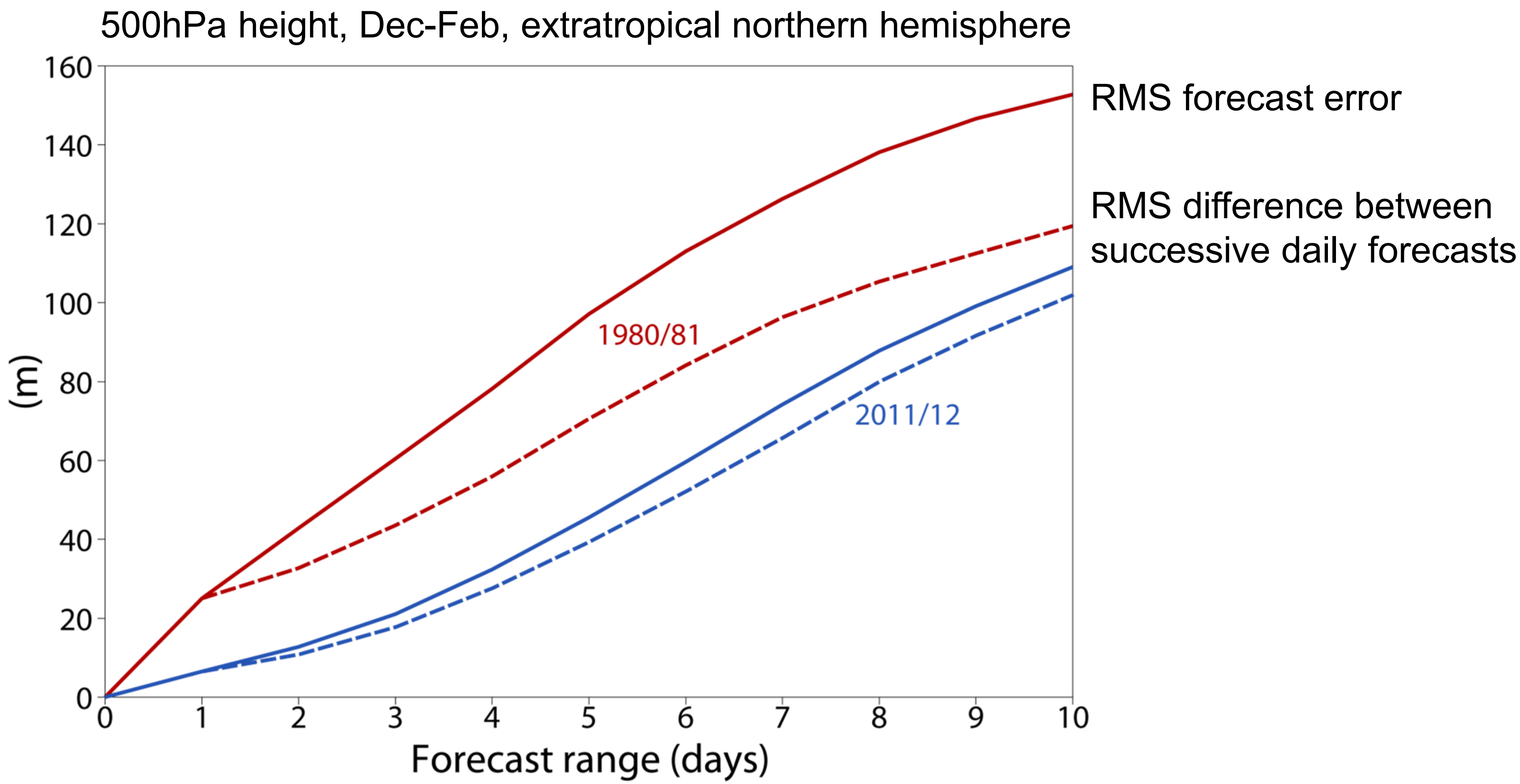
Potential for forecast improvement: arguments of Lorenz (1982)

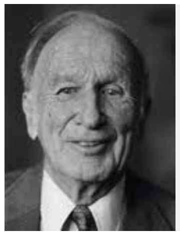




Lorenz: RMS difference curve is the limit of the forecast improvement that is possible without reducing the day-1 forecast error (assuming that the model has realistic intrinsic error-growth characteristics)

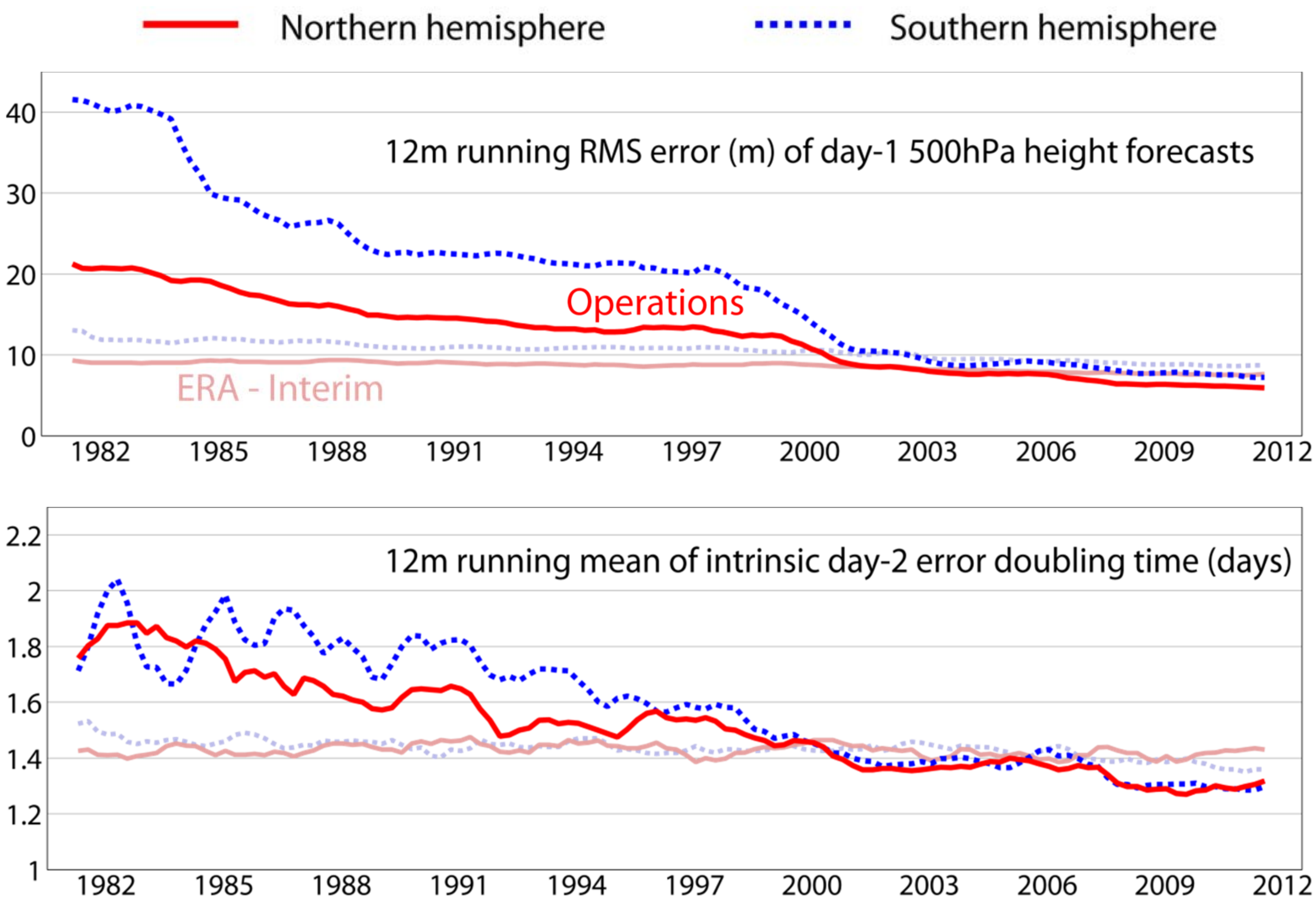
Potential for forecast improvement: arguments of Lorenz (1982)





Lorenz: RMS difference curve is the limit of the forecast improvement that is possible without reducing the day-1 forecast error (assuming that the model has realistic intrinsic error-growth characteristics)

Evolution of short-range forecast error and its intrinsic rate of growth



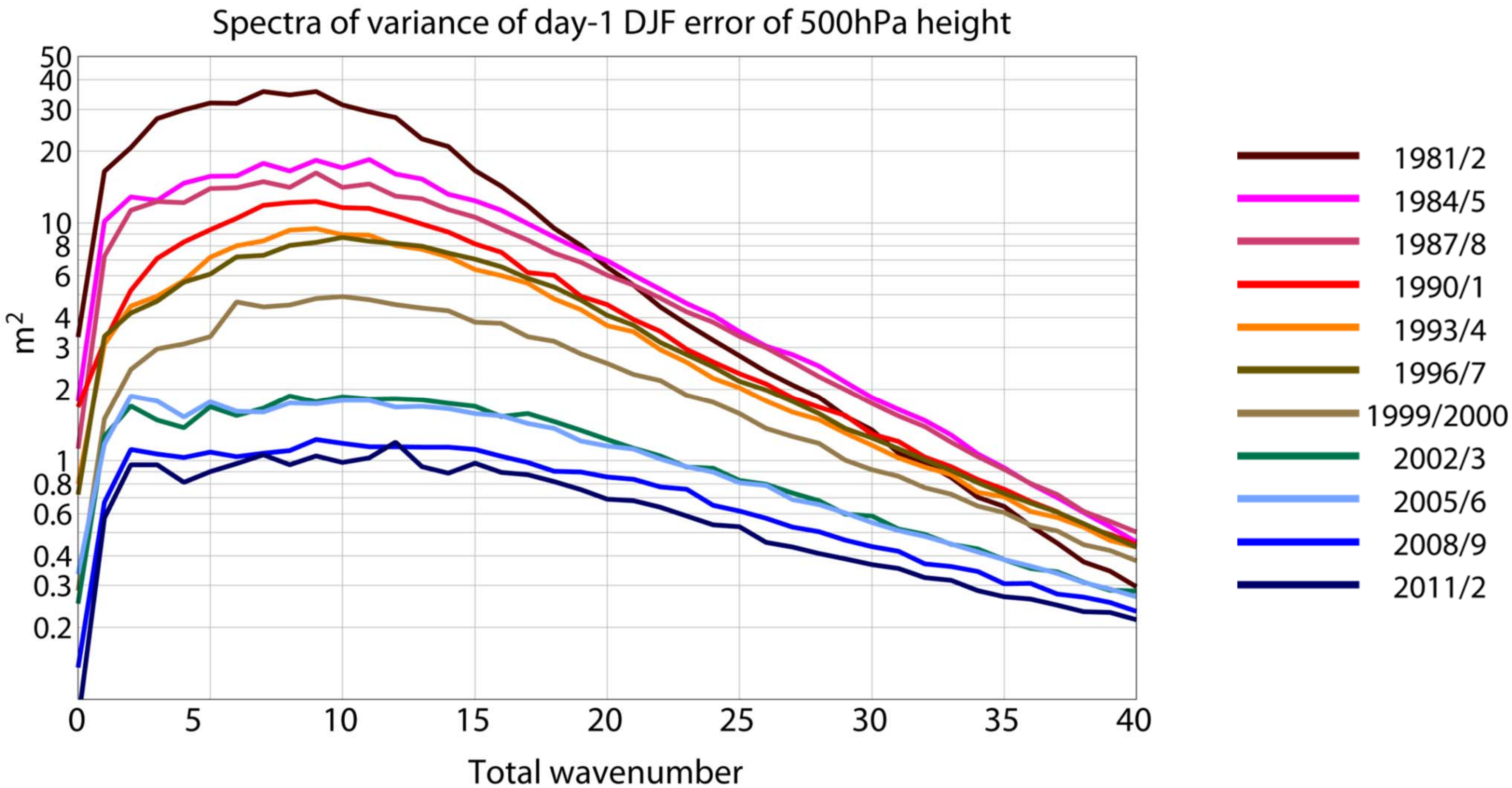
Intrinsic error growth is estimated from the difference between today's forecast and that made yesterday.

Lorenz employed a simple model of this error growth, since generalised by Dalcher and Kalnay (1987):

$$\frac{\partial E}{\partial t} = \gamma + \alpha E - \beta E^2$$

Reduction of one-day forecast error has been accompanied by a reduction in the time it takes for error to double in magnitude, particularly in the earlier years

Spectral characteristics of short-range forecast error



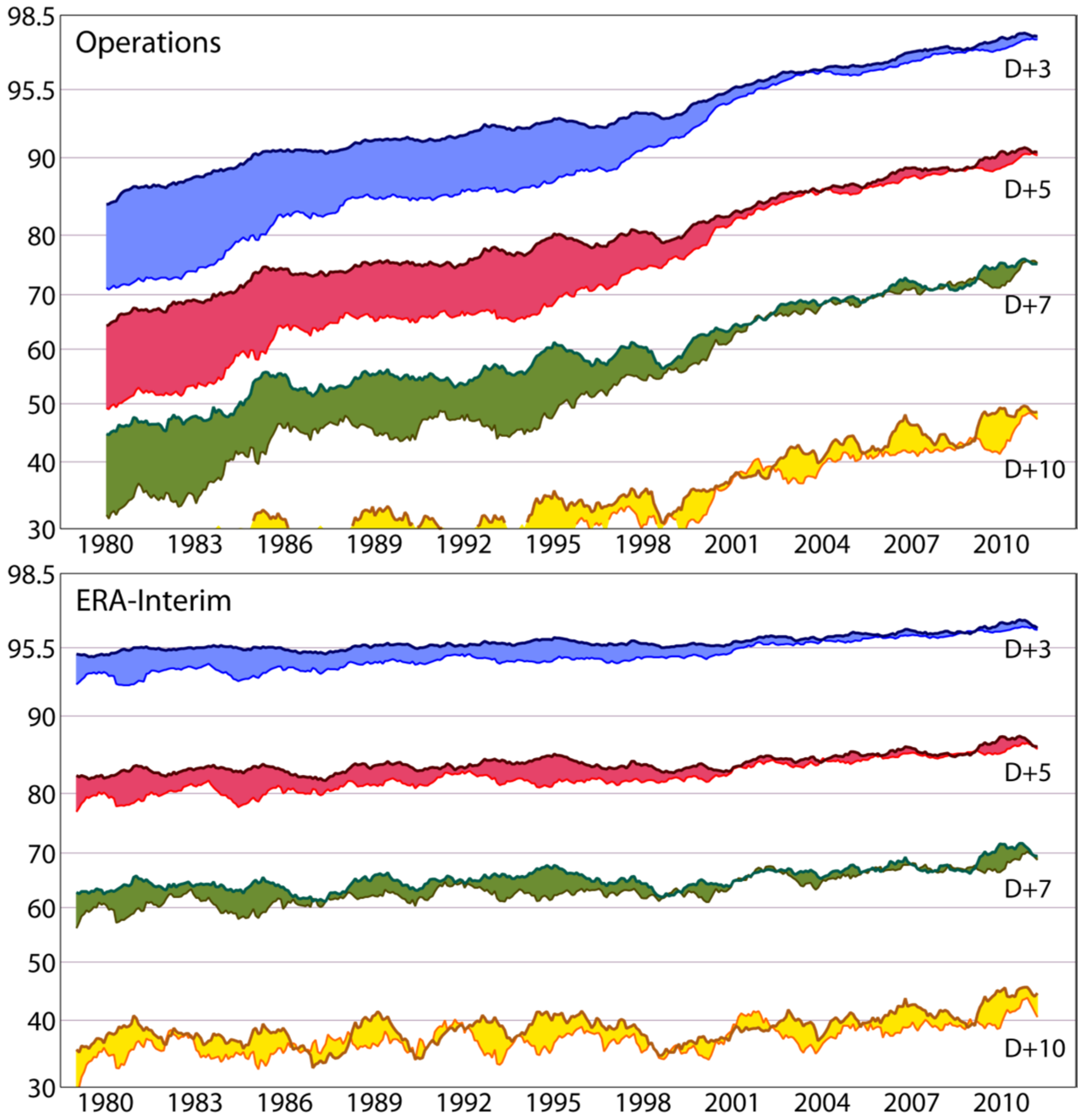
Since the late 1990s, improvement in short-range forecasts has occurred across the range of wavenumbers originally chosen for study by Lorenz

Evolution of the skill of forecasts

Correlation (%) of actual and predicted 500hPa height anomalies

(12-month running means)

Northern hemisphere
Southern hemisphere



Improvement in forecasts:

from 1980 to 2000 comes mostly from improvement to forecasting system

since 2000 comes from improvement to forecasting system and to observations

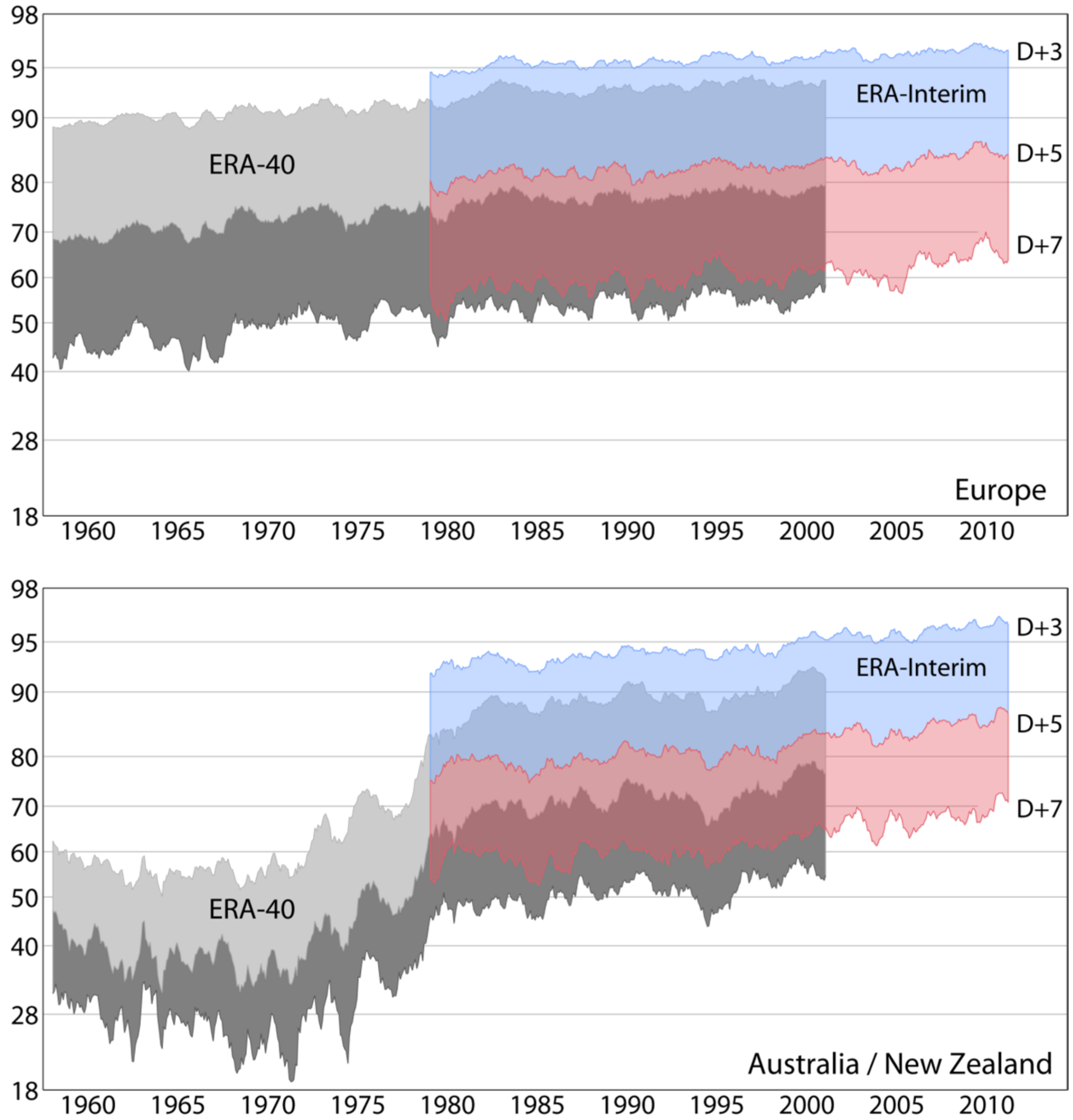
Evolution of the skill of forecasts

Correlation (%) of actual and predicted 500hPa height anomalies

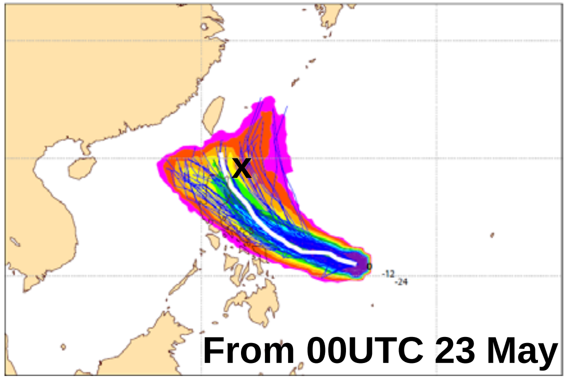
(12-month running means)

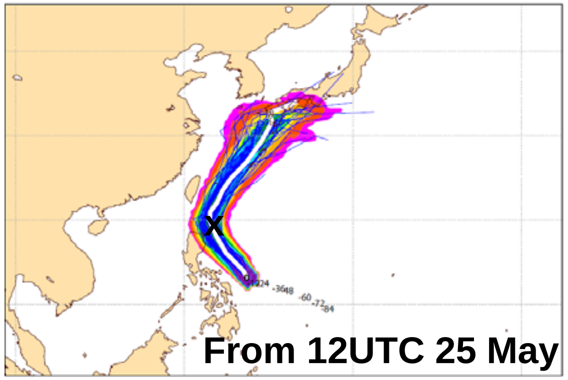
Verification is restricted to two regions that have been relatively well observed throughout the period from 1958 to the present

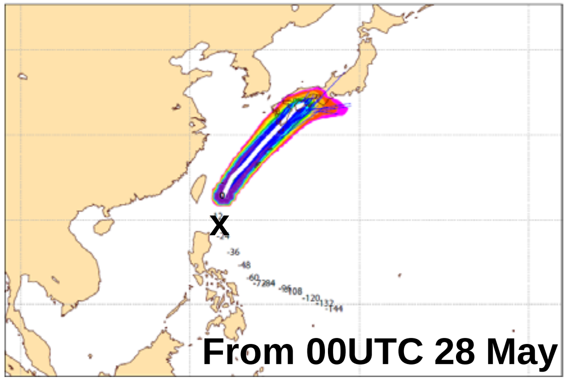
How much better would we do before 1979 with more-advanced (4D-Var, …) assimilation methods and better specifications of background and observation errors for the earlier period?

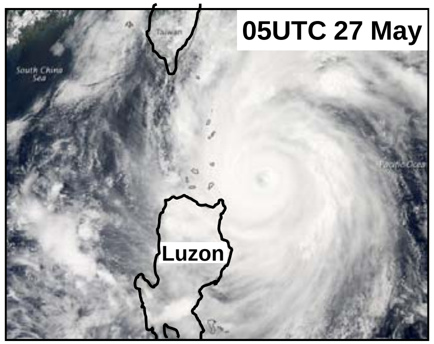


Tropical cyclone Songda – May 2011





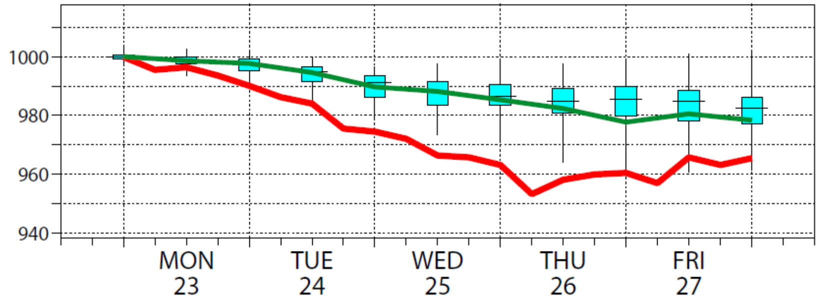


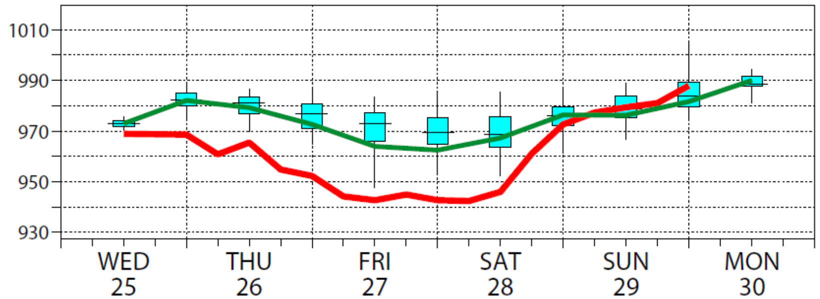


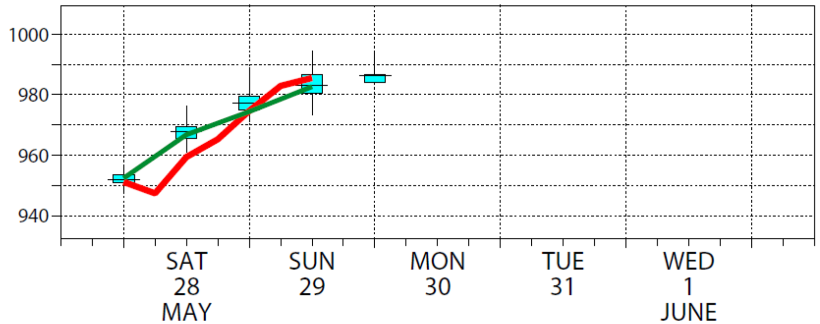
NASA Aqua MODIS

Cyclone tracks for up to five days from high-resolution (white) and ensemble forecasts

Central pressures
Red: High-resolution forecast (16km)
Green: Ensemble control (32km)

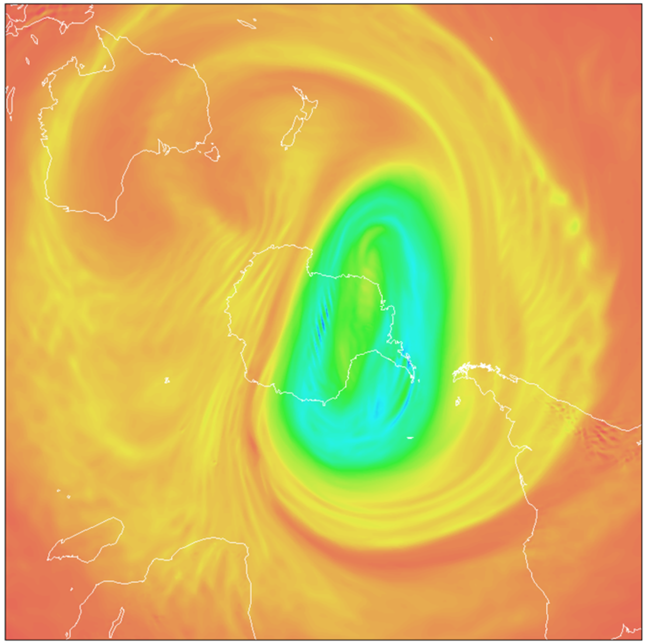






Break-up of the stratospheric polar vortex over southern hemisphere in September 2002

Potential vorticity at 850K 00UTC 2002/09/01



Operational analyses ~40km resolution

Splitting of vortex into two had never previously been observed in the southern hemisphere

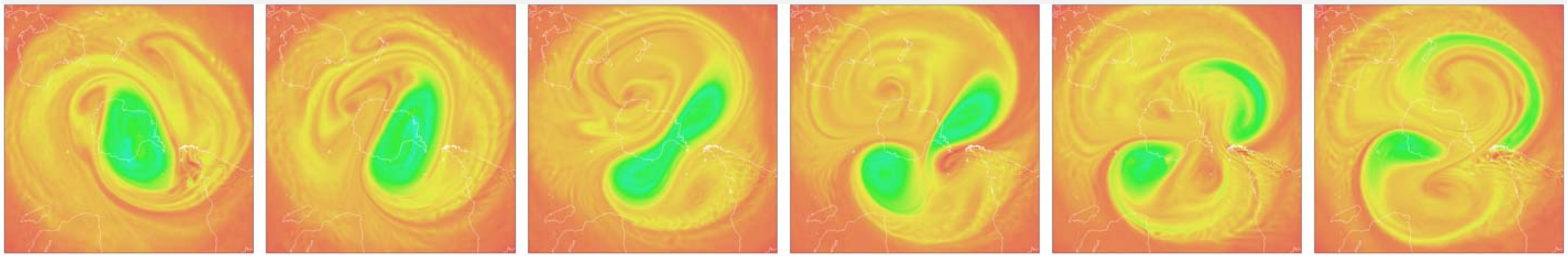
But was predicted a week or so in advance

A high point for the “rational solution of the problem of meteorological prediction” advocated by Bjerknes

Shown here for potential vorticity on the 850K isentropic surface, a quantity approximately conserved by motion on this surface

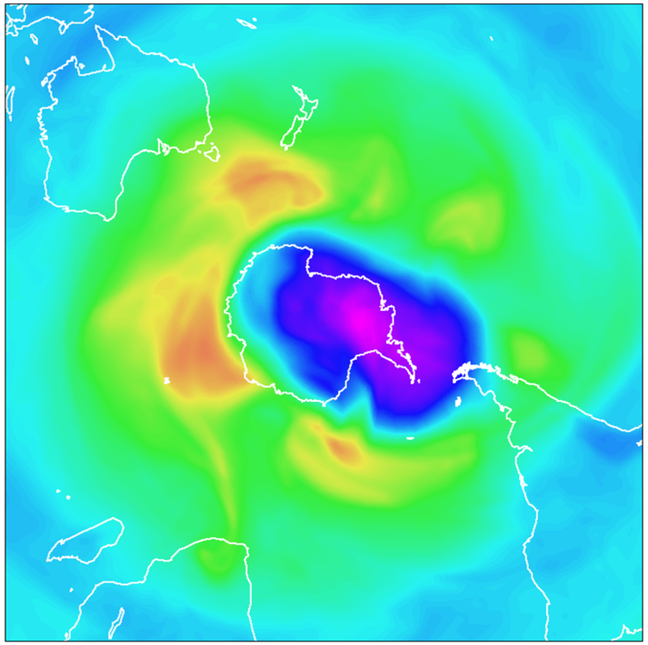
Operational ECMWF 850K PV forecast from 12UTC 19 September 2002

D+0 D+2 D+4 D+6 D+8 D+10



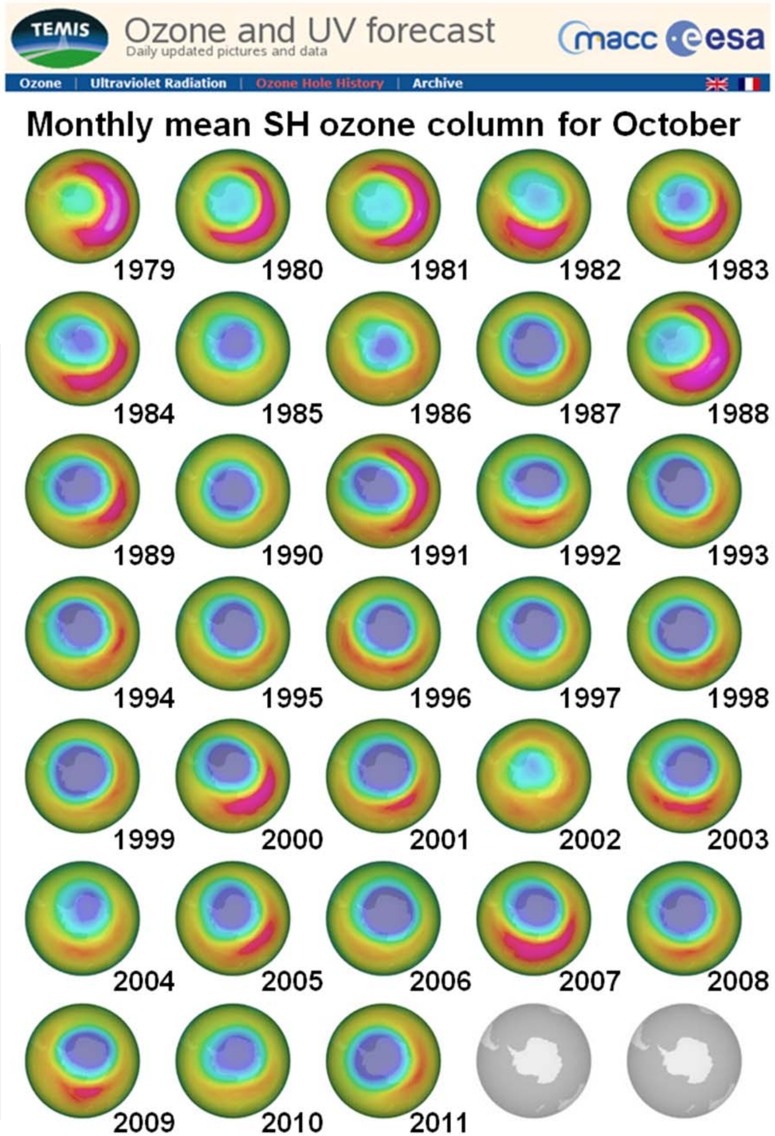
Filling of the stratospheric polar ozone hole over southern hemisphere in September 2002

Total column ozone 00UTC 2002/09/10



ERA-Interim analyses ~80km resolution

From KNMI multi-sensor reanalysis (van der A *et al*., 2010) of total column ozone, a contribution to the pilot EU GMES Atmosphere Monitoring Service



Some key sources of improvement

Better modelling

- basic to the process

Variational assimilation of fundamental measurements

- adjusting model variables to improve fit of model-equivalents to observed quantities (e.g. T and q so that simulated radiances match values measured by satellite)

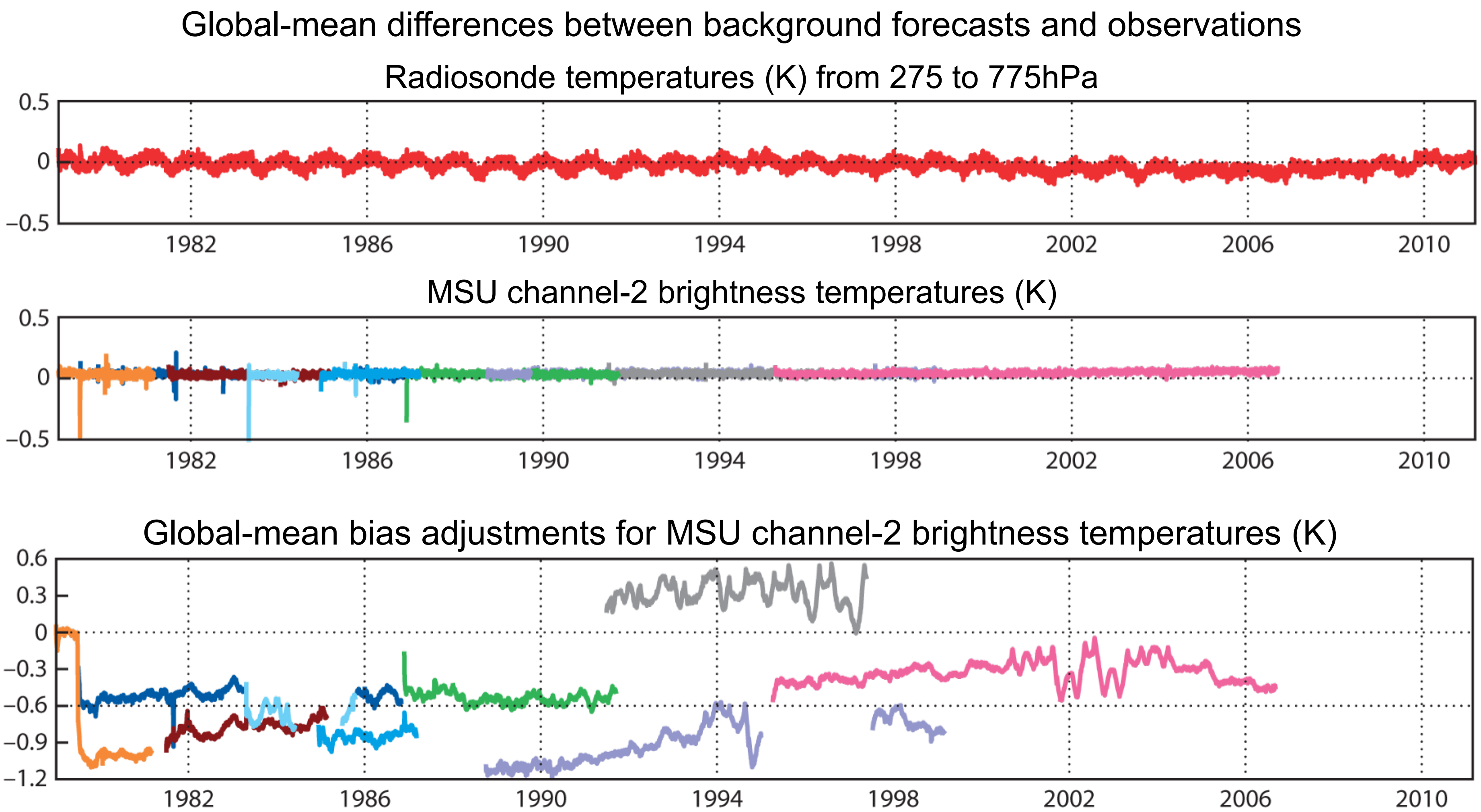
Better balance

- from the formulation of the background-error constraint, dynamical estimation of error statistics, ...

Better and more extensive bias adjustment of observations

- adjusts perceived biases in observations or model-equivalents
- is handled variationally for several data types, but anchored by other types (separately-adjusted radiosonde data, unadjusted uppermost satellite-sounding channels, ...)

Temporal consistency of ERA-Interim

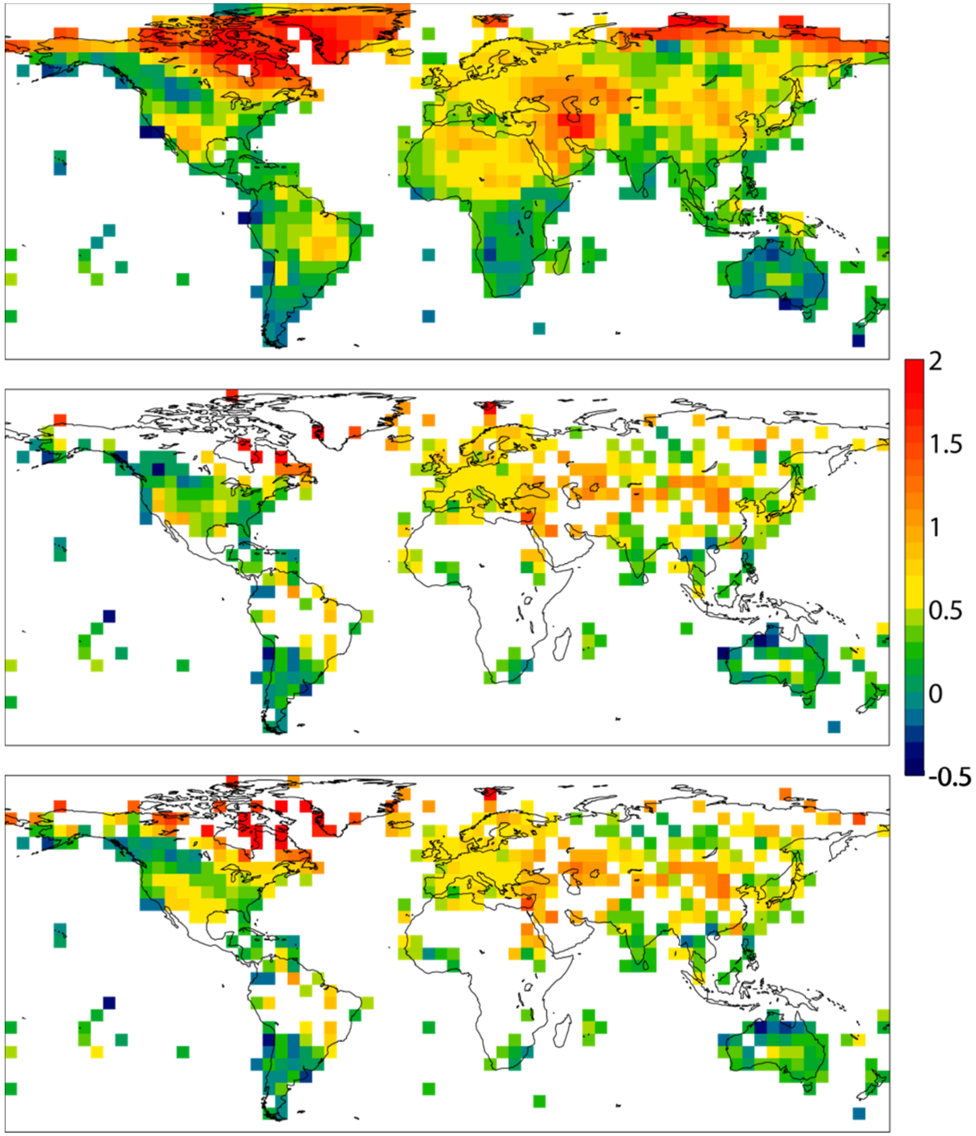


Radiosonde temperature adjustments follow Haimberger *et al*. (2008) and Andrae *et al*. (2004)

Monitoring large-scale temperature change

Differences in 16-year means of 2m temperature (K)

(1995 to 2010) – (1979 to 1994)



ERA-Interim (Dee *et al*., 2011)

ERA-Interim analyses synoptic observations using a model background

CRUTEM analyses monthly station data using station climate as background

CRUTEM3 (Brohan *et al*., 2006)

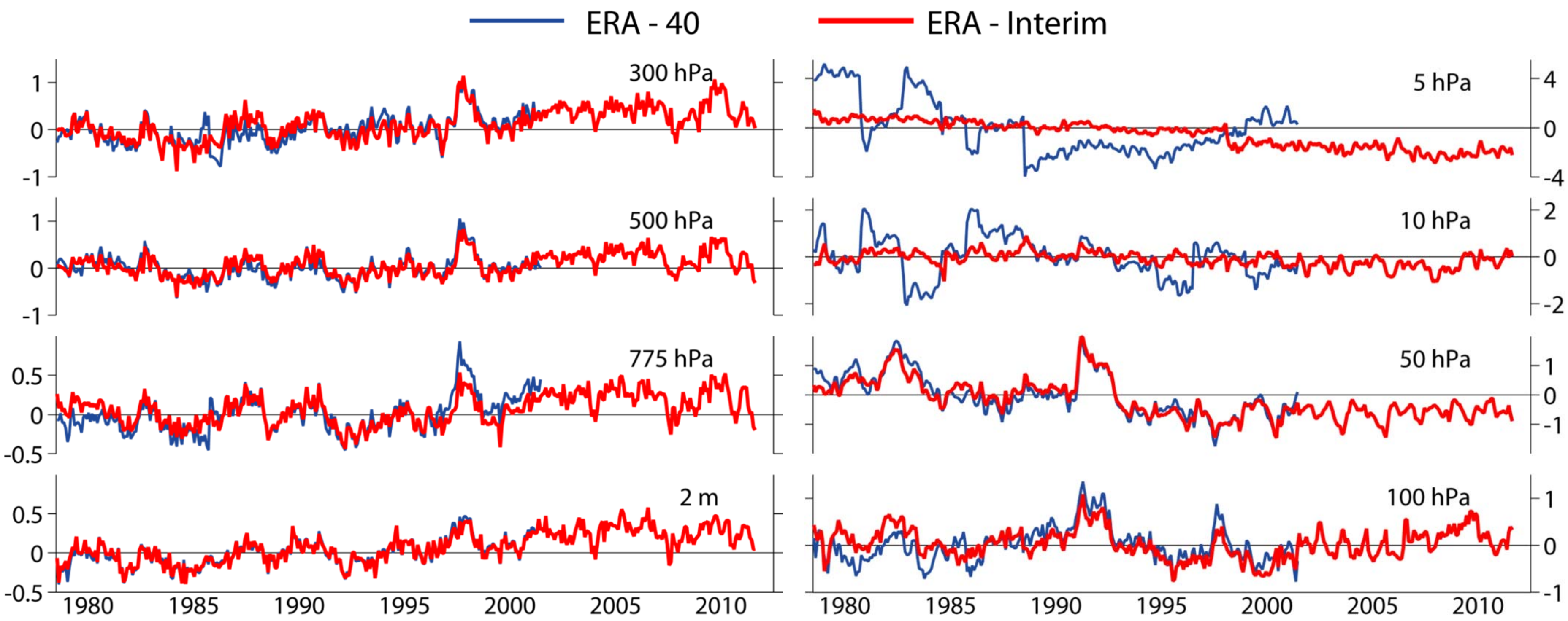
At common grid boxes, RMS differences between ERA-Interim and CRUTEM are:

0.241K for CRUTEM3

0.227K for CRUTEM4

CRUTEM4 (Jones *et al*., 2012)

Global-mean near-surface, tropospheric and stratospheric temperature anomalies (K)

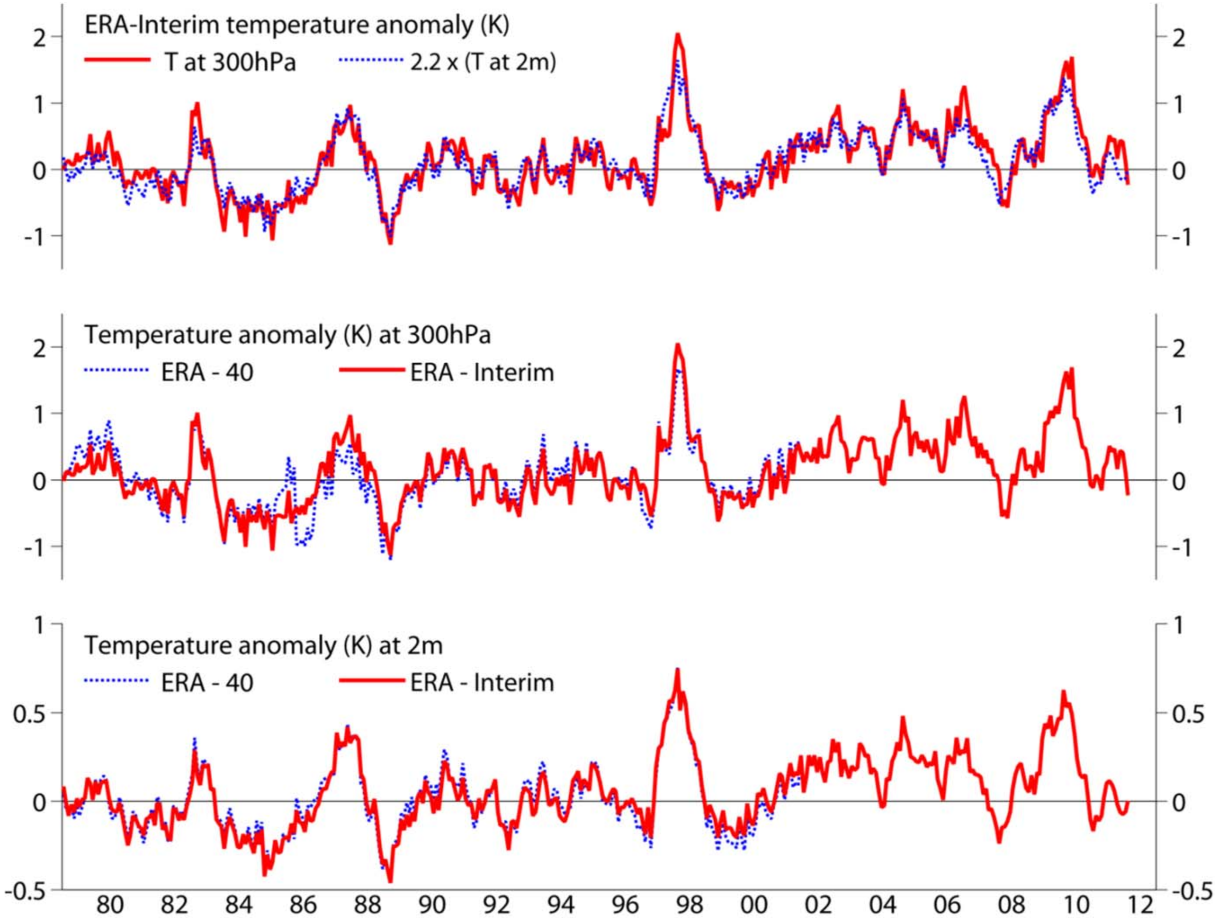


Tropospheric time series change little, but improve, from ERA-40 to ERA-Interim

ERA-Interim is much more consistent over time in mid to upper stratosphere, but it is hard to avoid a shift at high levels due to the change from SSU to AMSU

ERA-Interim also shifts near the tropopause due to increasing amounts of biased aircraft data and due to correction of model bias by recent GPS occultation data

Near-surface and upper-tropospheric tropical temperature anomalies



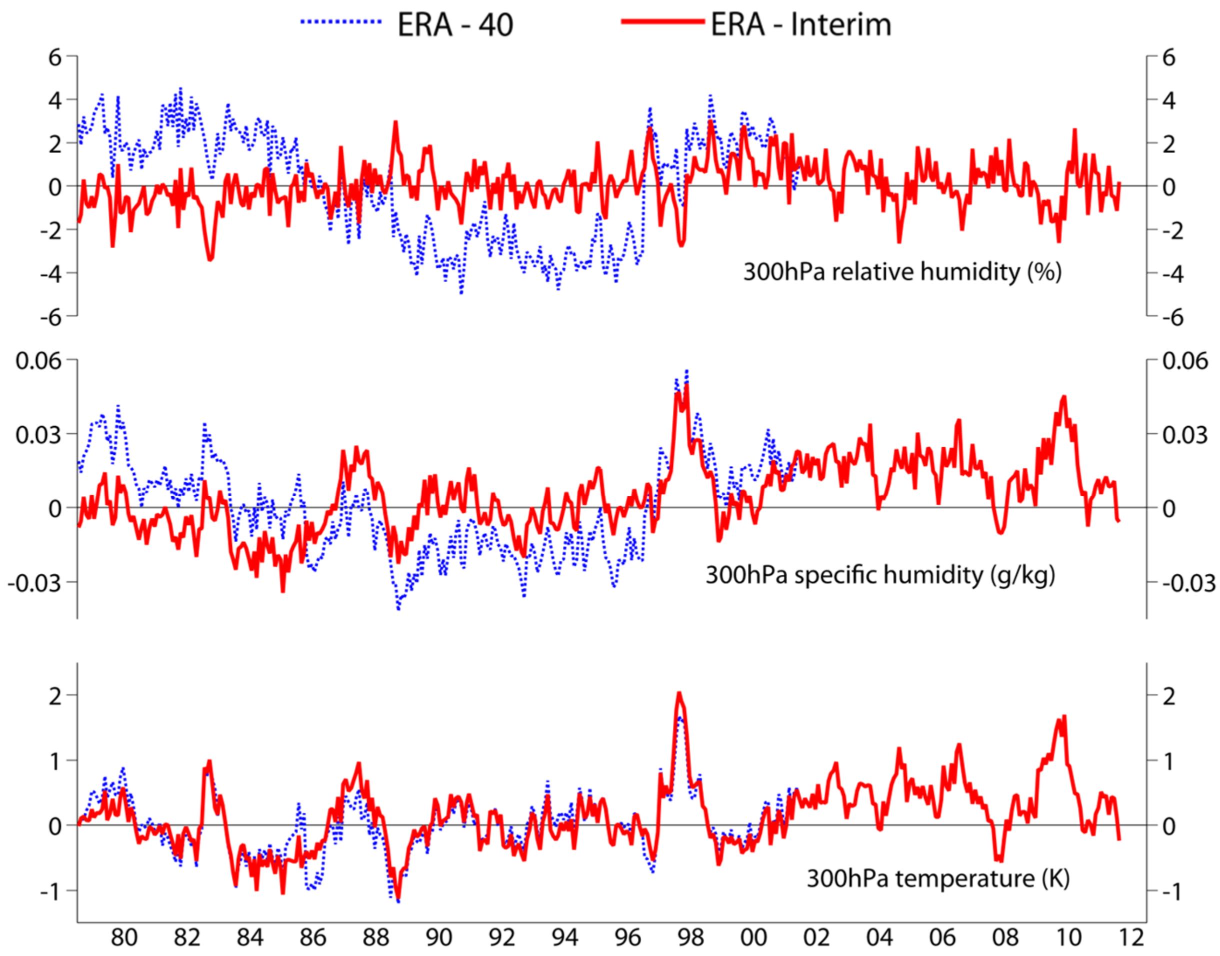
ERA shows strong correlation and amplification of anomalies by a factor ~2.2 from the surface to the tropical upper troposphere

Consistent with longstanding model results but not raw radiosonde data

Under study by Haimberger using adjusted radiosonde temperatures

ERA satellite bias adjustments need to be checked against independent estimates

Relative humidity, specific humidity and temperature in the tropical upper troposphere



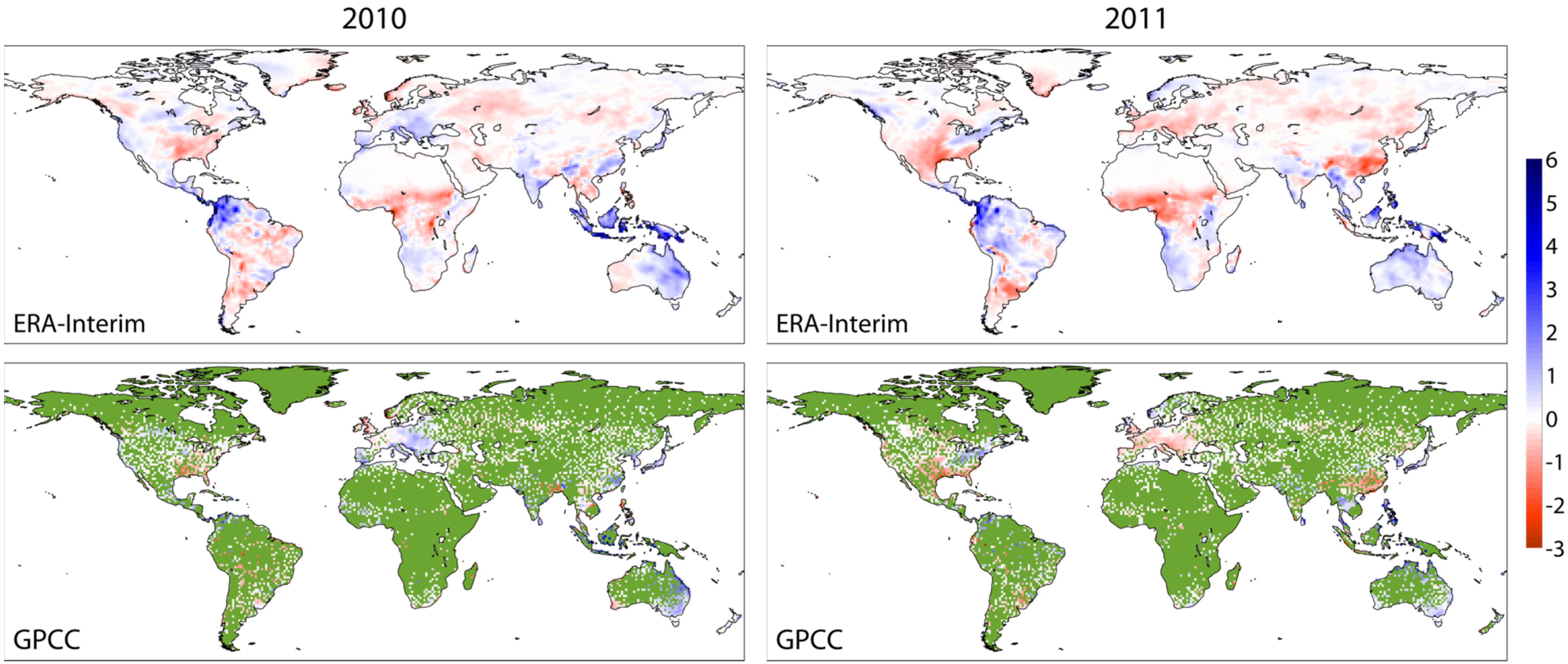
ERA-Interim has strong correlation between temperature and specific humidity anomalies in the tropical upper troposphere

Relative humidity is quite uniform over time in ERA-Interim, especially early on

ERA-Interim is much more consistent over time than ERA-40

Despite improvements, problems remain in assimilating satellite humidity data at lower levels over the tropical oceans

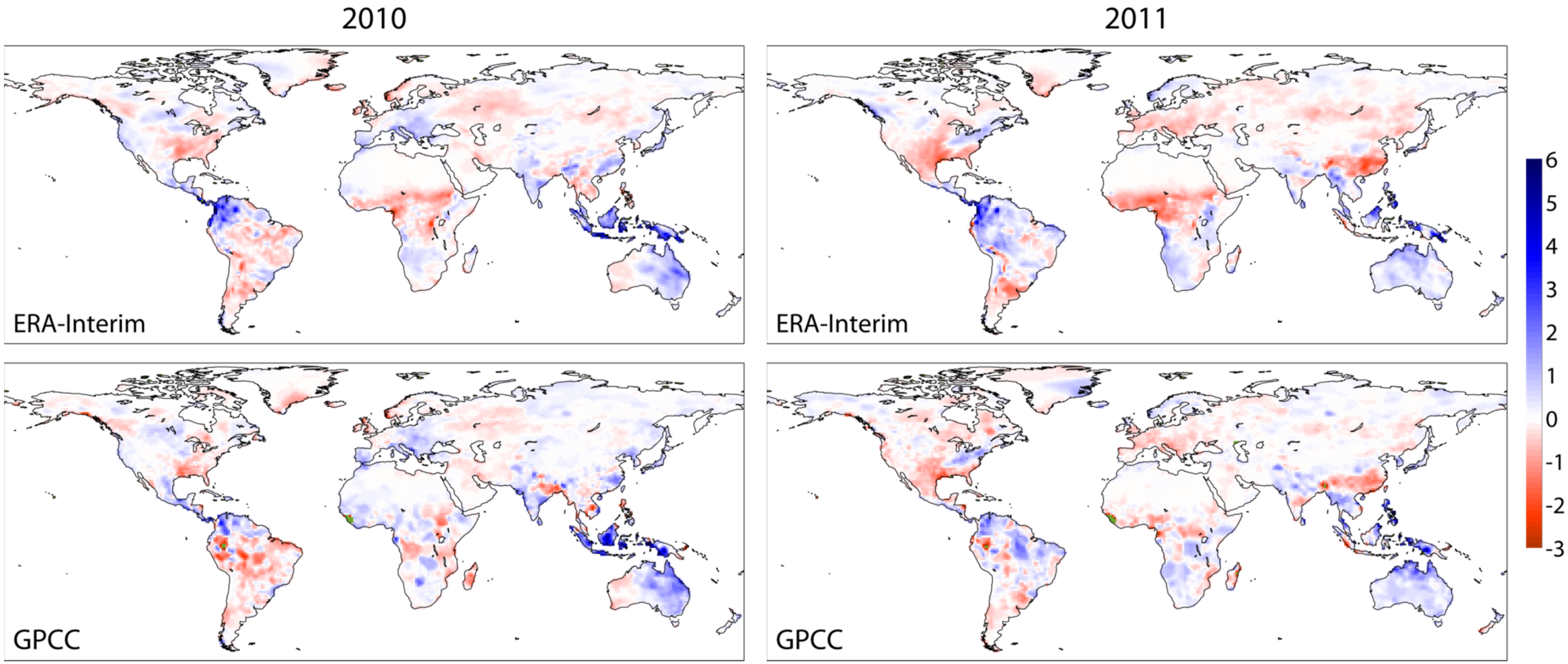
Annual anomalies in precipitation (mm/day) for 2010 and 2011 relative to 1980-2009 mean



ERA-Interim uses no rain-gauge data

Anomalies computed from the monthly rain-gauge analyses of the Global Precipitation Climatology Centre (GPCC) at Deutscher Wetterdienst are plotted for $1^{O}x1^{O}$ grid boxes that contain data from at least one gauge for every month in 2010 and 2011 respectively

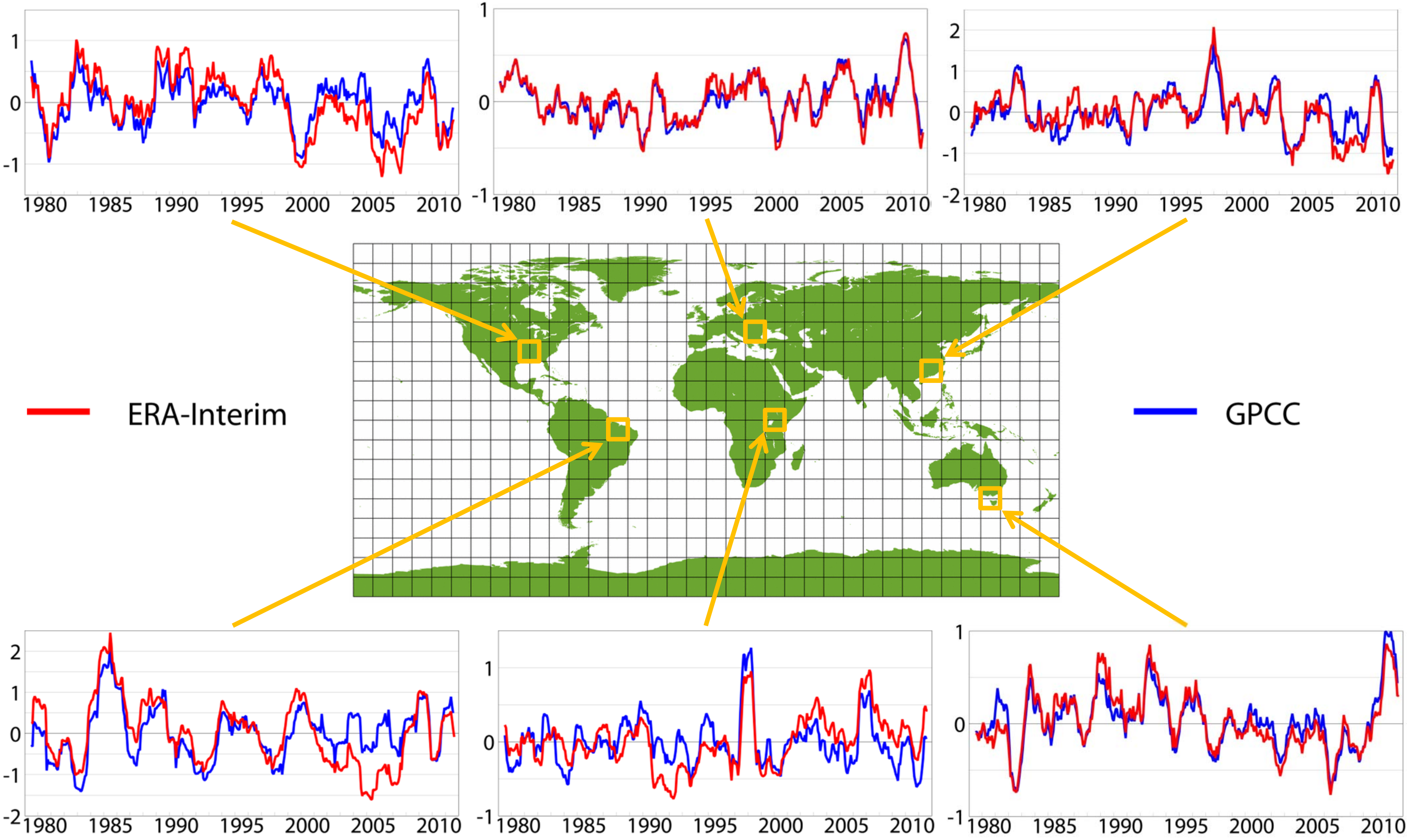
Annual anomalies in precipitation (mm/day) for 2010 and 2011 relative to 1980-2009 mean



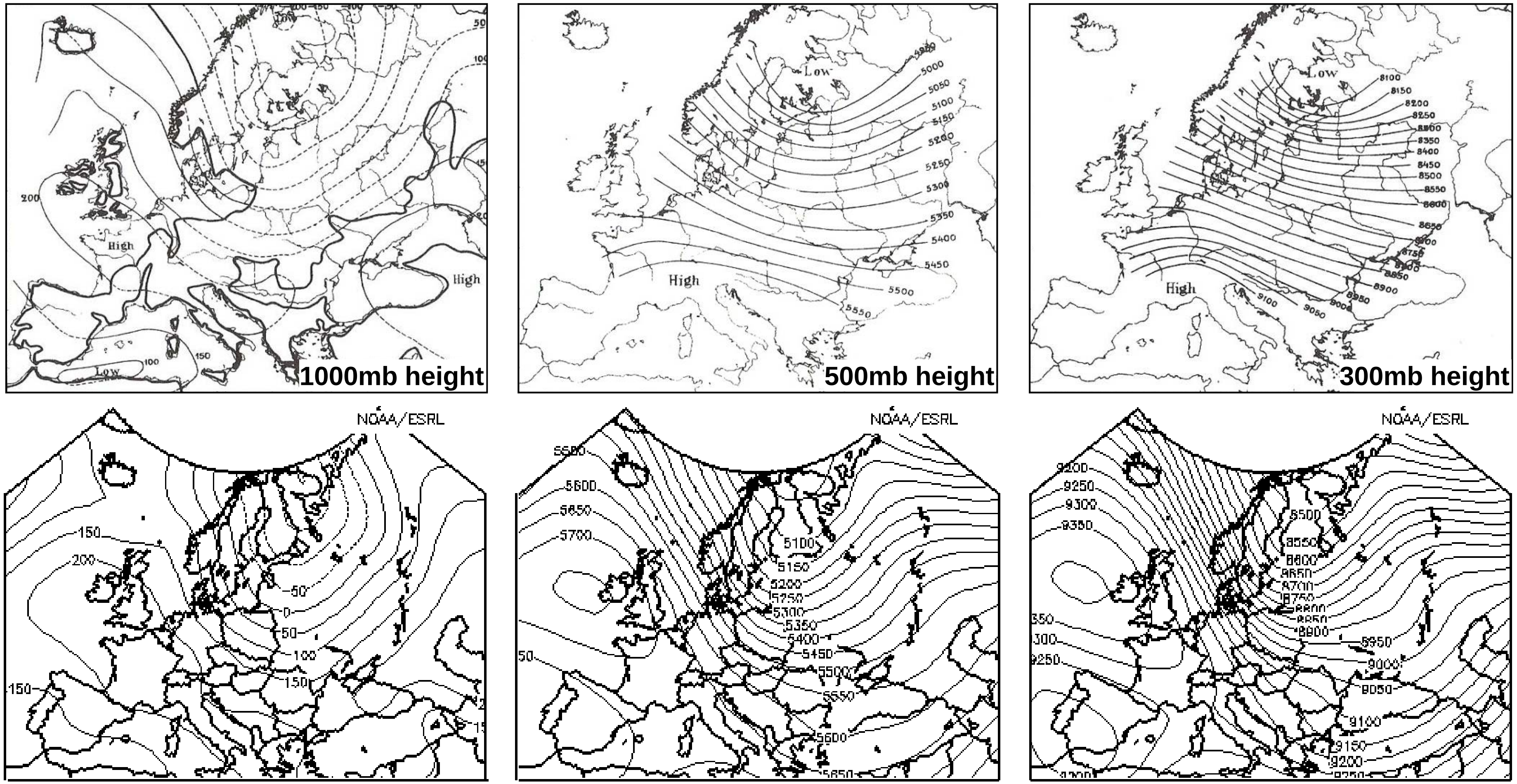
ERA-Interim uses no rain-gauge data

Anomalies computed from the monthly rain-gauge analyses of the Global Precipitation Climatology Centre (GPCC) at Deutscher Wetterdienst are plotted for all 1^{O}x1^{O} grid boxes for which values are provided by the GPCC

12-month running-mean precipitation anomalies (mm/day) for six 10^{O}x10^{O} domains



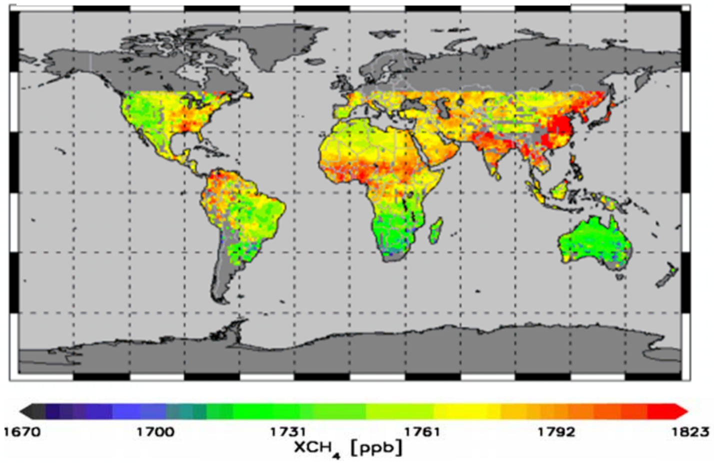
Pioneering isobaric weather maps
7 November 1901 revisited



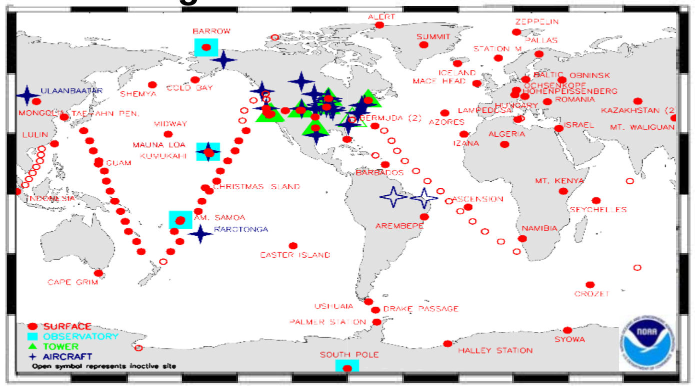
Compo *et al*. (2011) have applied modern ensemble techniques to assimilate surface-pressure data from the late 19th Century onwards. Version-2 analyses from NOAA/ESRL for 12 UTC 7 November 1901 are shown. Contour intervals differ by a factor ~0.98.

Estimating emissions: methane from July 2009 to June 2010

ESA/SCIAMACHY satellite data

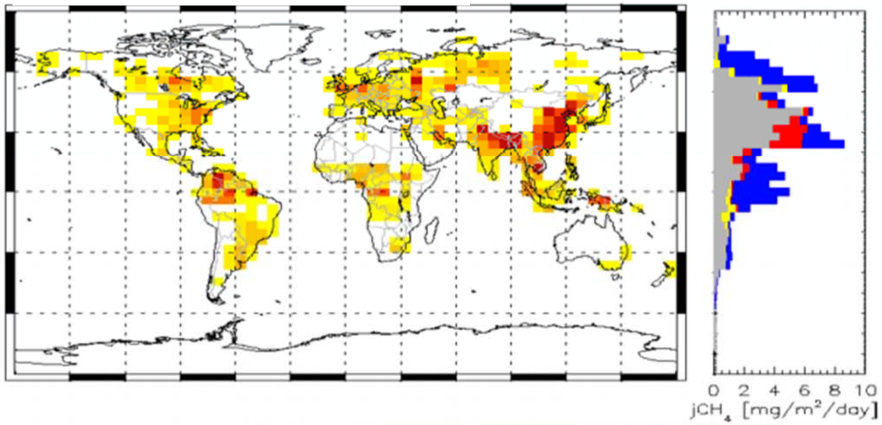


Anchoring flask data



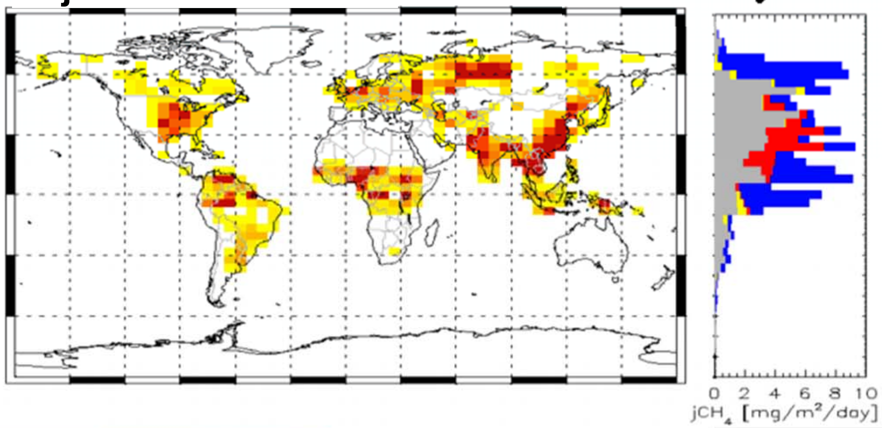
NOAA Earth System Research Laboratory global cooperative air sampling network

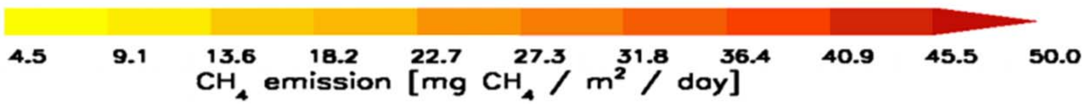
Prior modelled emissions



Adjusted emissions

July 2009





A contribution to the pilot EU GMES Atmosphere Monitoring Service, from Peter Bergamaschi, JRC

In conclusion

Observations are vital for weather forecasting and climate monitoring

- but how they are used in the provision of products and services is vital too

Much has been achieved from developments in global data assimilation

- with substantial resulting forecast improvements
- with improving capability (and a large user community) for reanalysis
- perhaps beyond expectations at the outset, in both cases

Much remains to be achieved, in particular through

- further model refinement (from weather elements to planetary scale)
- ensemble assimilations for error specification and initiating ensemble forecasts
- extension of assimilation window – likely to be of particular benefit for reanalysis
- continuing attention to improvement and extension of use of observational data

and through continuing development of coupled components

- for ocean circulation and surface waves, and land-surface conditions
- for trace gases and aerosols , especially to provide GMES atmospheric services

Acknowledgments and thanks

To co-authors:

and many others …

Addendum

The PowerPoint version of this presentation,

including animations, is available from:

ftp://ftp.ecmwf.int/pub/Simmons/