Improving the Prognostic Ozone Parameterization in the NCEP GFS and CFS for Climate Reanalysis and Operational Forecasts

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Stratospheric Ozone

- A key radiatively active constituent in both solar and infrared radiation
- Affects temperature of stratosphere, troposphere, and surface
- Reduces harmful ultraviolet light reaching surface
- Ozone variations play role in climate variability of Northern and Southern Hemisphere
- Reanalysis systems, and the weather models on which they rely, must accurately represent the ozone field and its effect on climate variations.
- Complete ozone photochemistry is too computationally intensive to include in current weather and climate models
- So, parameterize processes!

Naval Research Laboratory CHEM2D Ozone Photochemistry Parameterization (CHEM2D-OPP, *McCormack et al. (2006)*)

CHEM2D-OPP is based on gas-phase chemistry circa 2000.
Same approach as used in ECMWF IFS (*Cariolle and Deque 1986*).
Includes ozone depletion from CFCs.

Net ozone photochemical tendency

functional form of Production *P* minus Loss *L*

$$\frac{d\chi_{O_3}}{dt} = (P-L)\left[\chi_{O_3}, T, c_{O_3}\right]$$

Approximate as Taylor series linearized about reference state (denoted by overbar).

$$\frac{\partial\chi}{\partial t}(P-L) = (P-L)_0 + \left.\frac{\partial(P-L)}{\partial\chi_{O3}}\right|_0 \left(\chi_{O3} - \bar{\chi}_{O3}\right) + \left.\frac{\partial(P-L)}{\partial T}\right|_0 \left(T - \bar{T}\right) + \left.\frac{\partial(P-L)}{\partial c_{O3}}\right|_0 \left(c_{O3} - \bar{c}_{O3}\right)$$

χ_{O3} prognostic Ozone mixing ratio

T Temperature

c_{O3} column ozone

Partial use of CHEM2D-OPP in the current NCEP Global Forecast System (GFS) atmosphere/land model

$$\frac{\partial \chi}{\partial t}(P-L) = (P-L)_0 + \left.\frac{\partial (P-L)}{\partial \chi_{O3}}\right|_0 \left(\chi_{O3} - \bar{\chi}_{O3}\right)$$

Reference tendency $(P\text{-}L)_0$ and all partial derivatives are computed from odd oxygen (Ox ≡ O_3+O) reaction rates in the CHEM2D photochemical transport model.

CHEM2D is a global model extending from the surface to ~120 km that solves 280 chemical reactions for 100 different species within a transformed Eulerian mean framework with fully interactive radiative heating and dynamics.

The partial CHEM2D-OPP is used in the 20th Century Reanalysis (20CR) and operational NCEP system, and atmosphere of Climate Forecast System (CFS) Reanalysis (CFSR) and operational CFSv2.

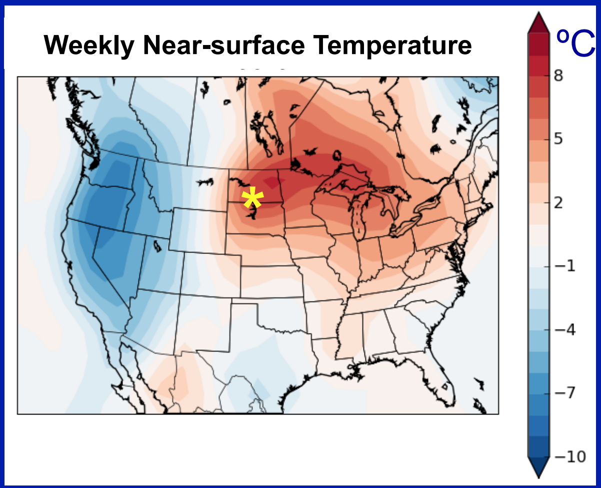
χ_{O3}	prognostic Ozone mixing ratio
T	Temperature
c_{O3}	column ozone

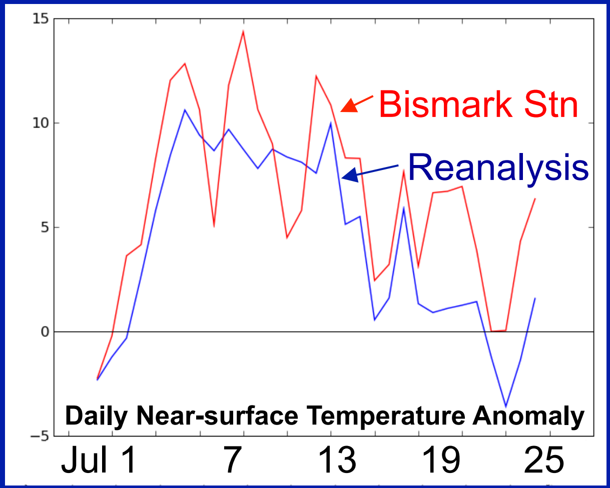
The 20th Century Reanalysis Project version 2 (1871-2011)

Summary: An international project led by NOAA and CIRES to produce *4-dimensional* reanalysis datasets for climate applications extending back to the 19th century using an Ensemble Kalman Filter and *only surface pressure observations.*

Weekly-averaged anomaly during July 1936 United States Heat Wave (997 dead during 10-day span)

Daily variations compare well with in-situ data.





The reanalyses provide:

-First-ever estimates of near-surface to tropopause 6-hourly fields extending back to the beginning of the 20th century;

-Estimates of uncertainties in the basic reanalyses and derived quantities (e.g., storm tracks).

Examples of uses:

- Validating climate models.
- Determining storminess and storm track variations.
- Understanding historical climate variations (e.g., 1930s Dust Bowl, 1920-1940s Arctic warming).
- Estimating risks of extreme events

Support from US Dept of Energy Office of Science (BER), NOAA Climate Program Office

Compo et al. 2011

Ensemble Filter Algorithm (Whitaker and Hamill, 2002)

Ensemble mean

$$\overline{\mathrm{x}}_j^{\mathrm{a}} = \overline{\mathrm{x}}_j^{\mathrm{b}} + \mathrm{K}\left(y^{\mathrm{o}} - \overline{y}_j^{\mathrm{b}}\right),$$

Ensemble deviations

$$\mathrm{x}_j'^{\mathrm{a}} = \mathrm{x}_j'^{\mathrm{b}} - \tilde{\mathrm{K}}\left(y_j'^{\mathrm{b}}\right),$$

Sample Kalman Gain

$$\mathrm{K} = \mathrm{P}^{\mathrm{b}}\mathrm{H}^{\mathrm{T}}(\mathrm{H}\mathrm{P}^{\mathrm{b}}\mathrm{H}^{\mathrm{T}} + R)^{-1}$$

$$= \frac{1}{n-1}\sum_{j=1}^{n} \mathrm{x}_j'^{\mathrm{b}} y_j'^{\mathrm{b}} \left(\frac{1}{n-1}\sum_{j=1}^{n} y_j'^{\mathrm{b}} y_j'^{\mathrm{b}} + R\right)^{-1}$$

Sample Modified Kalman Gain

$$\tilde{\mathrm{K}} = \left(1 + \sqrt{\frac{R}{\mathrm{H}\mathrm{P}^{\mathrm{b}}\mathrm{H}^{\mathrm{T}} + R}}\right)^{-1} \mathrm{K},$$

$\mathbf{x}_j = \mathbf{x} + \mathbf{x}'_j$ is pressure, air temperature, winds, humidity, etc. at all levels and gridpoints, every six hours.

y^o is only observations of hourly and synoptic **surface pressure**,

$\mathbf{y}^b = \mathbf{H}\mathbf{x}^b$ is guess surface pressure

20th Century Reanalysis implementation of Ensemble Filter Algorithm

(Whitaker et al. 2004, Compo et al. 2006, Compo et al. 2011)

Algorithm uses an ensemble of GCM runs to produce the weight **K** that varies with the atmospheric flow and the observation network every 6 hours

Using 56 member ensemble, HadISST1.1 prescribed SST and sea ice monthly boundary conditions (*Rayner et al. 2003*)

1871-2011: T62, 28 level NCEP GFS08ex atmosphere/land model

9 hour forecasts for 6 hour centered analysis window

- time-varying CO_2, solar and volcanic radiative forcing
- prognostic stratospheric ozone

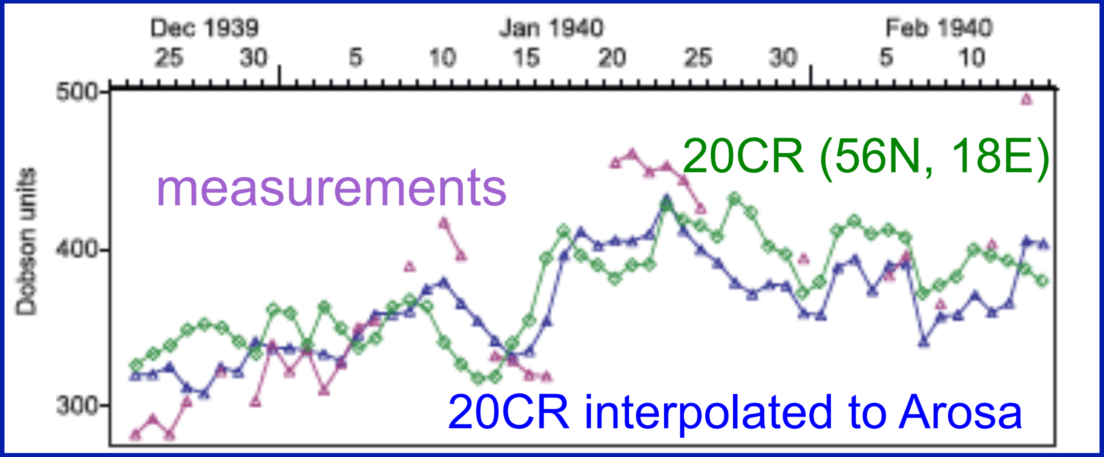
Sampling and Model error parameterizations:

-Covariance localization (4000 km, 4 scale heights) and

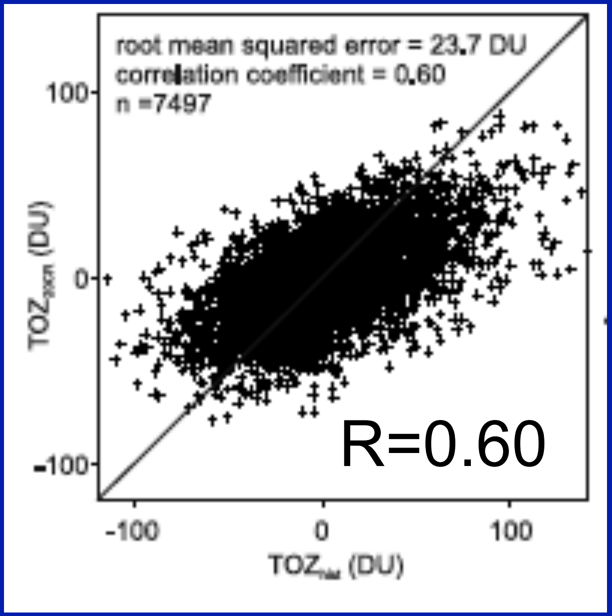
-Latitude and time dependent multiplicative covariance inflation (alpha = 1.01 to 1.12) [*Anderson and Anderson, 1999*; *Houtekamer and Mitchell, 2001; Hamill et al. 2001; Whitaker et al., 2004*]

http://go.usa.gov/XTd Compo et al. 2011, doi:10.1002/qj.776

Daily column ozone measurements and 20CR daily ozone at Arosa, Switzerland (46.8N, 9.7E)

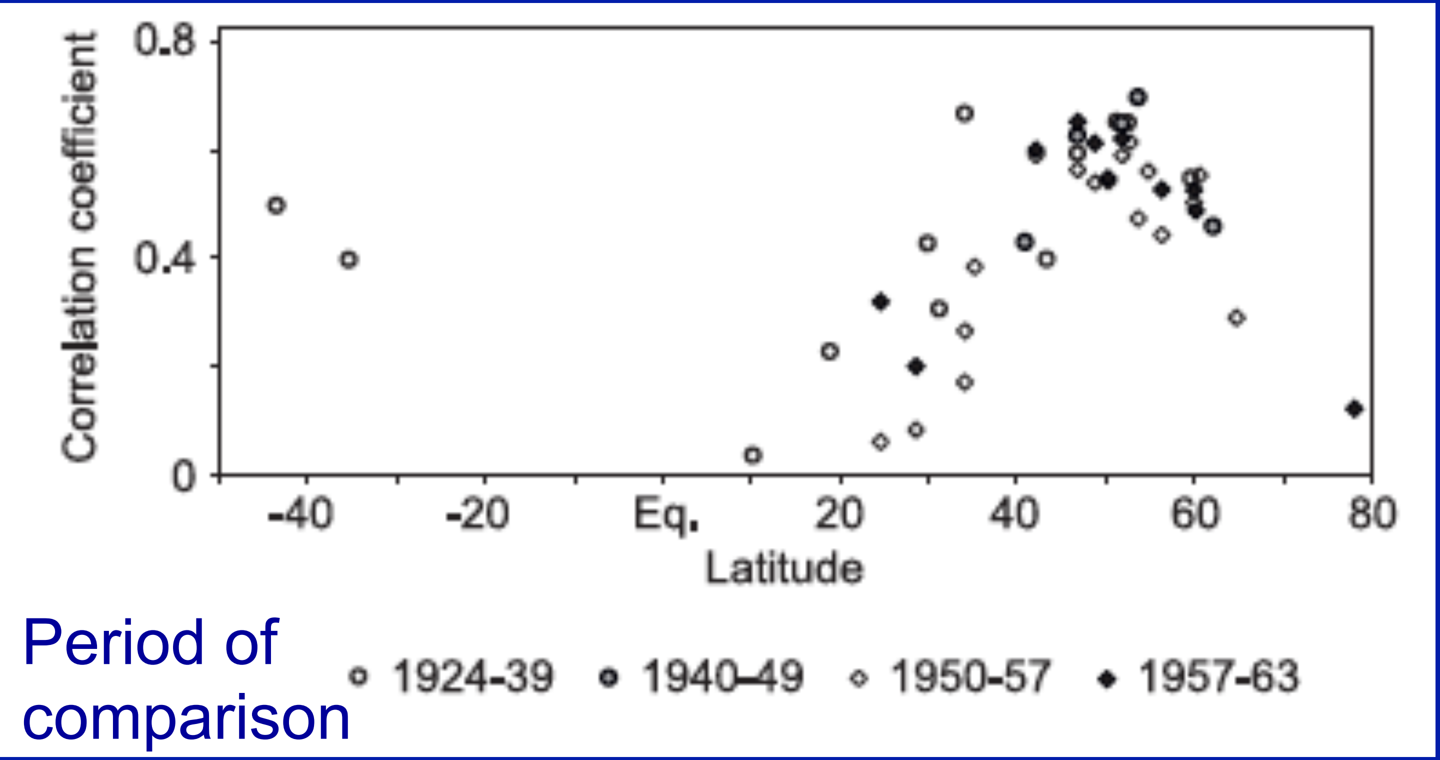


Anomaly comparison spanning 1924 to 1963



20CR ozone field has large scale fluctuations that reflect ozone highs associated with, e.g., cold air outbreaks (*Brönnimann and Compo 2012*).

Column ozone from stations compared to 20CR



High correlations in Northern Hemisphere midlatitudes where dynamics are an important contributor to ozone variations. Correlations are consistent with measurements taken throughout the record.

[(Brönnimann and Compo 2012)](#)

Issue: Reference state ozone, temperature, and CHEM2D-OPP parameterization coefficients include the chemistry arising from CFCs throughout the 1871-2011 20CR record.

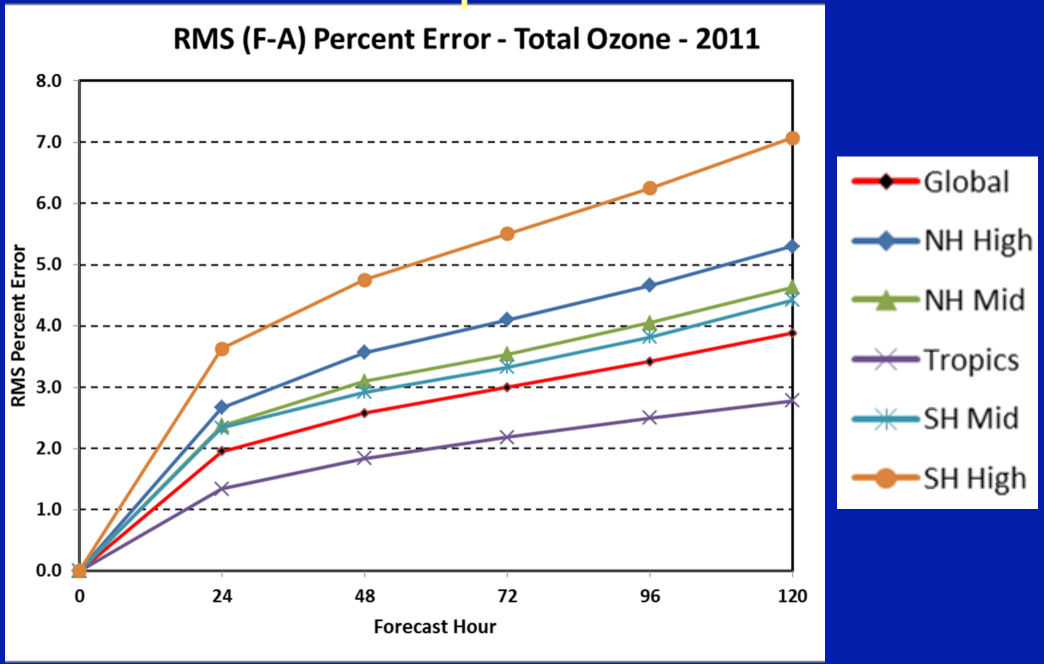
Project: new CHEM2D-OPP coefficients and an appropriate ozone climatology will be generated for the period before widespread CFC usage.
Test effects on 20CR fields by comparing to historical ozone observations and to upper-air temperature observations.

But: Inclusion of CFC in early 20th century is probably not the whole story.

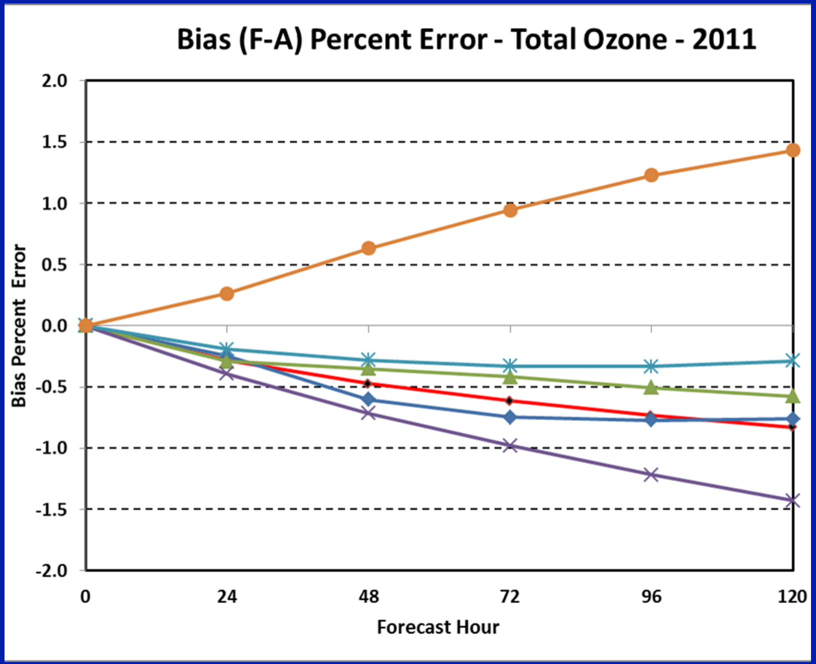
Some of the issues seen in 20CR ozone likely relate to an effect seen in operational GFS ozone forecasts.

GFS ozone forecast skill for 2011

Root Mean Square Error



Bias



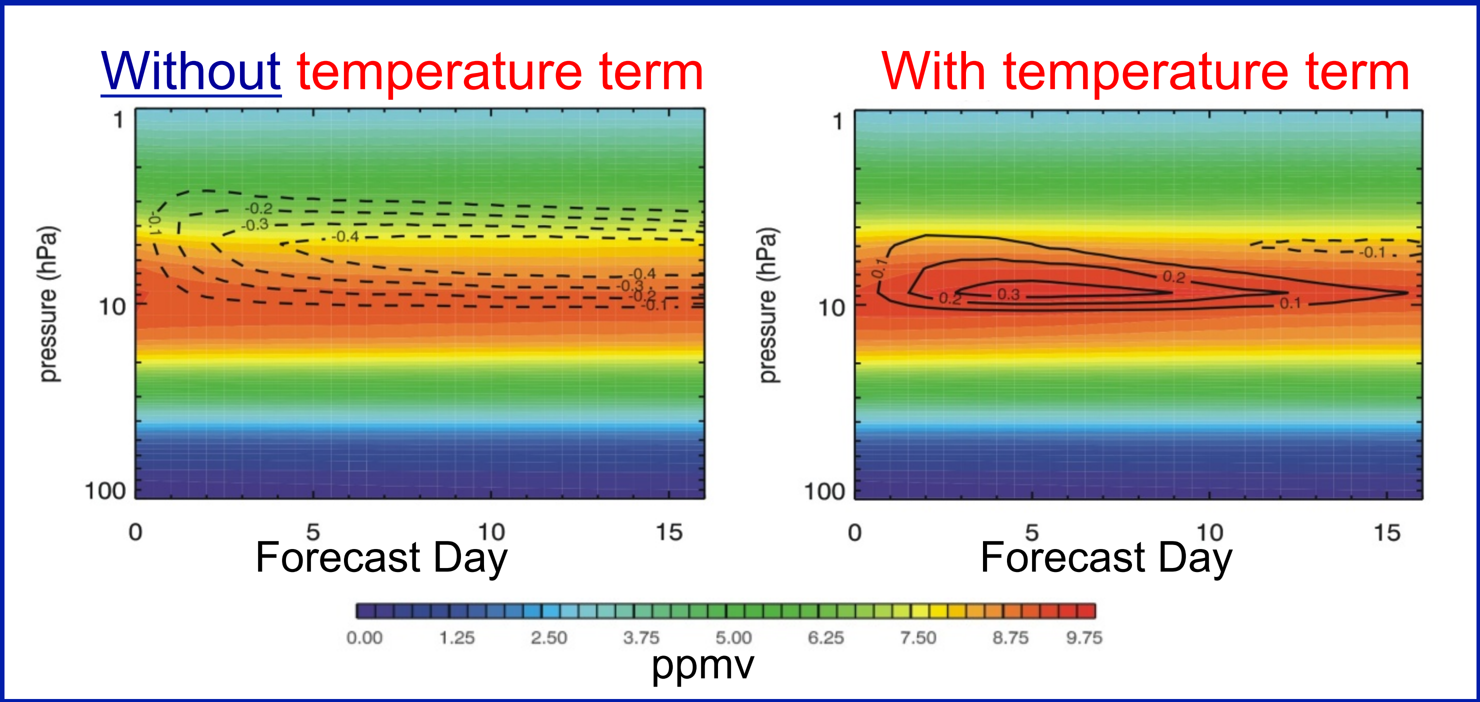
GFS ozone forecast skill degrades significantly after 5 days due, in part, to unrealistic losses over most of the globe resulting in a global negative bias.

Why the loss of ozone?

Long et al. 2013

Forecasts of Equatorial Stratospheric O_3 mixing ratios using NOGAPS-ALPHA model with and without CHEM2D-OPP temperature term (June)

$$\frac{\partial \chi}{\partial t}(P-L) = (P-L)_0 + \left.\frac{\partial (P-L)}{\partial \chi_{O3}}\right|_0 \left(\chi_{O3} - \bar{\chi}_{O3}\right) + \left.\frac{\partial (P-L)}{\partial T}\right|_0 \left(T - \bar{T}\right)$$



Line Contours show O_3 tendency (dashed= Loss)

Adding temperature term should significantly reduce unrealistic loss in GFS-type implementation

χ_{O3} prognostic Ozone mixing ratio
T Temperature
c_{O3} column ozone

McCormack et al. 2013

Goal: Improve and reduce the errors in the weather and climate variability of the NOAA GFS model with a particular focus on the stratosphere.

Benefit to the NOAA Climate Reanalysis system (Kumar et al. Type I proposal) and NCEP operational forecasts from

Improved treatment of stratospheric ozone by fully utilizing all 4 terms of CHEM2D-OPP.

Improved treatment of stratospheric ozone by accounting for the effect of the time-variation of CFCs in the parameterization.

Improved treatment of stratospheric water vapor by including a realistic climatology.

Questions?

Project Plans

- Implement more advanced O_3 parameterization using the full CHEM2D-OPP and an improved treatment of stratospheric water vapor for use in new versions of the GFS, CFS, and next generation NOAA climate reanalysis systems.

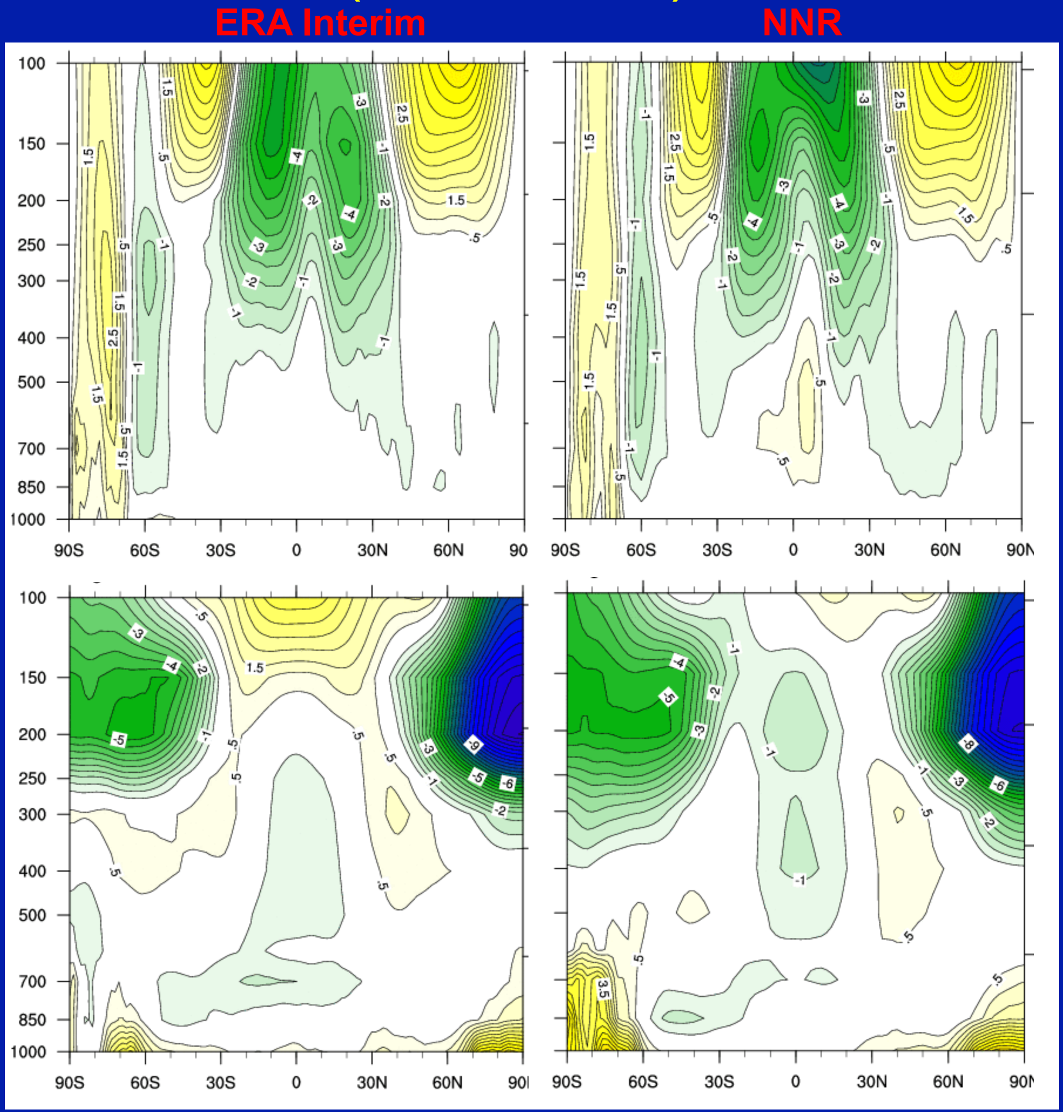
- The O_3 parameterization will include the effect of changes in temperature, changes in the vertical distribution of O_3, and the time-variation of CFCs.

- The upgraded parameterization and new climatology will be tested in climate reanalyses and weather and climate simulations.

- As a first step, the parameterization will be tested with two modes, one for times before CFCs and one for times after CFCs began to be released in large quantities.

- Also implement a new stratospheric H_2O climatology as a necessary first step toward future implementation of parameterized H_2O photochemistry.

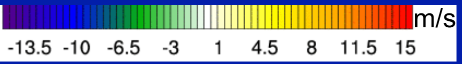
Zonal mean of annual differences between 20CR, ERA-Interim and NNR (1981-2010)



200

Zonal wind

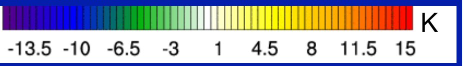
1000



200

Air Temperature

1000



CI:0.5 m/s

Biases Over Poles and Stratosphere

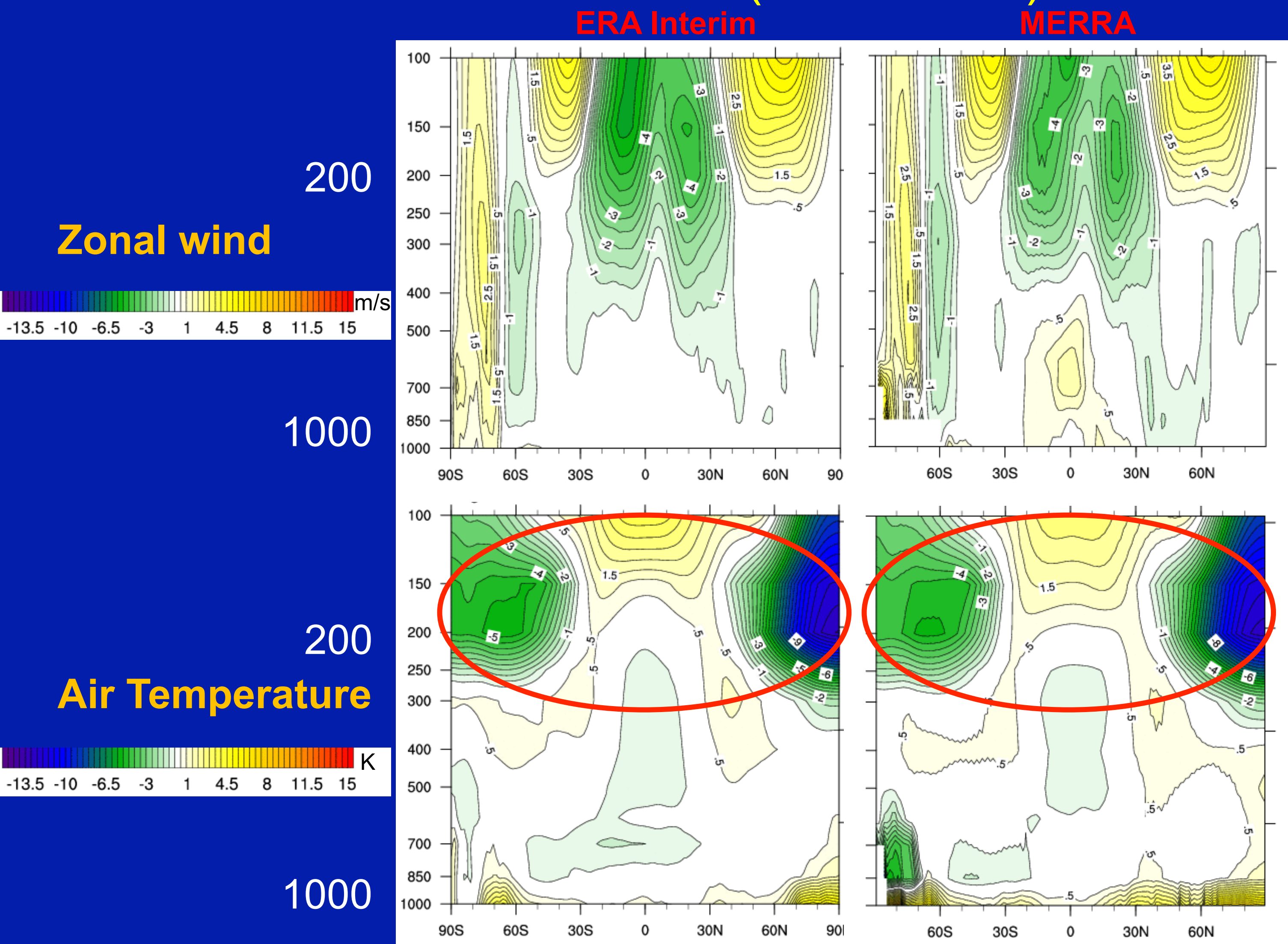
CI:0.5 K

Courtesy of new NOAA-CIRES WRIT tool (C. Smith)

20CR tropospheric biases are low and tend to be closer to ERA-Interim. They are sometimes of opposite sign.

Adapted from Compo et al. (2011)

Zonal mean of annual differences between 20CR, ERA-Interim and MERRA (1981-2010)



CI:0.5 m/s

Biases Over Poles and Stratosphere

CI:0.5 K

Courtesy of new [NOAA-CIRES WRIT](#) tool (C. Smith)

20CR stratospheric biases are large and tend to be slightly closer to MERRA. Sign of biases is similar.

Adapted from Compo et al. (2011)