Assimilation of Middle Atmosphere Observations

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Outline

NOGAPS-ALPHA

- *Advanced Level Physics High-Altitude* (ALPHA) prototype extension of the *Navy Operational Global Atmospheric Prediction System* (NOGAPS)
- Motivation for Upward Extension
- R&D History
- Additions to the **Forecast Model** & **Data Assimilation System**

Forecast Model

- hybrid vertical coordinates
- nonorographic gravity-wave drag
- non-LTE longwave radiative cooling
- fast O_3 and H_2O photochemistry

Data Assimilation System

- MLS/SABER temperatures
- MLS water vapor and ozone
- GPS RO stratospheric bending angle
- AIRS/AMSU stratospheric radiances

- Validation of and Science using the ~0-100 km NOGAPS-ALPHA DAS Products

NOGAPS-ALPHA Transitions to Operational NOGAPS

- Recent Transitions and Future Plans

Definitions/Nomenclature

NOGAPS

- The complete NWP system run *operationally* at the Fleet Numerical Meteorology and Oceanography Center (FNMOC)

Forecast Model

- Eulerian, hydrostatic, spectral
- Finite-difference L-grid vertical
- Central in time
- Semi-implicit time scheme
- Robert (Asselin) time filter

Data Assimilation System

NAVDAS: NRL Atmospheric 3DVAR DAS

- Operational October 2003

NAVDAS-AR (Accelerated Representor)

- NRL 4DVAR DAS
- Operational 23 September 2009

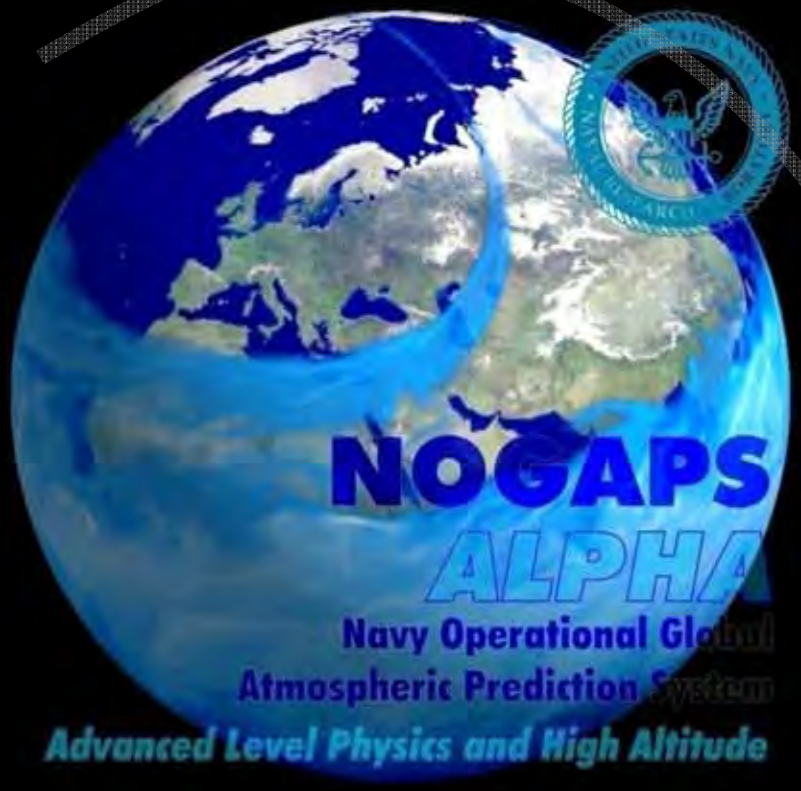
NOGAPS-ALPHA

- The R&D *nonoperational* high-altitude NOGAPS prototype run at NRL
- Usually lags the current NOGAPS tropospheric technology by 2-4 years in focusing on development of new stratospheric and mesospheric features
- More limited HPC resources, so run at lower horizontal resolution (e.g., T79)

2. Hybrid Vertical Coordinate

3. Nonorographic Gravity Wave Drag

1. Motivation & R&D History



4. Ozone Assimilation

9. Summary & Outlook

5. Water Vapor Assimilation

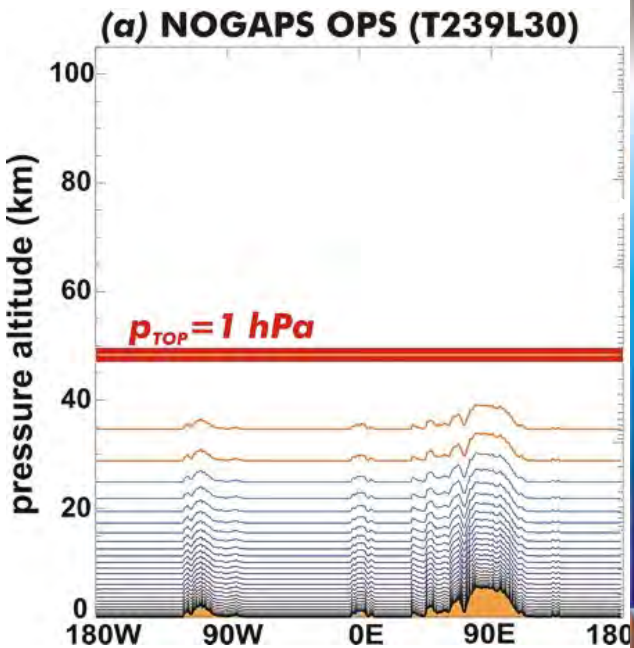
8. Operational Transitions

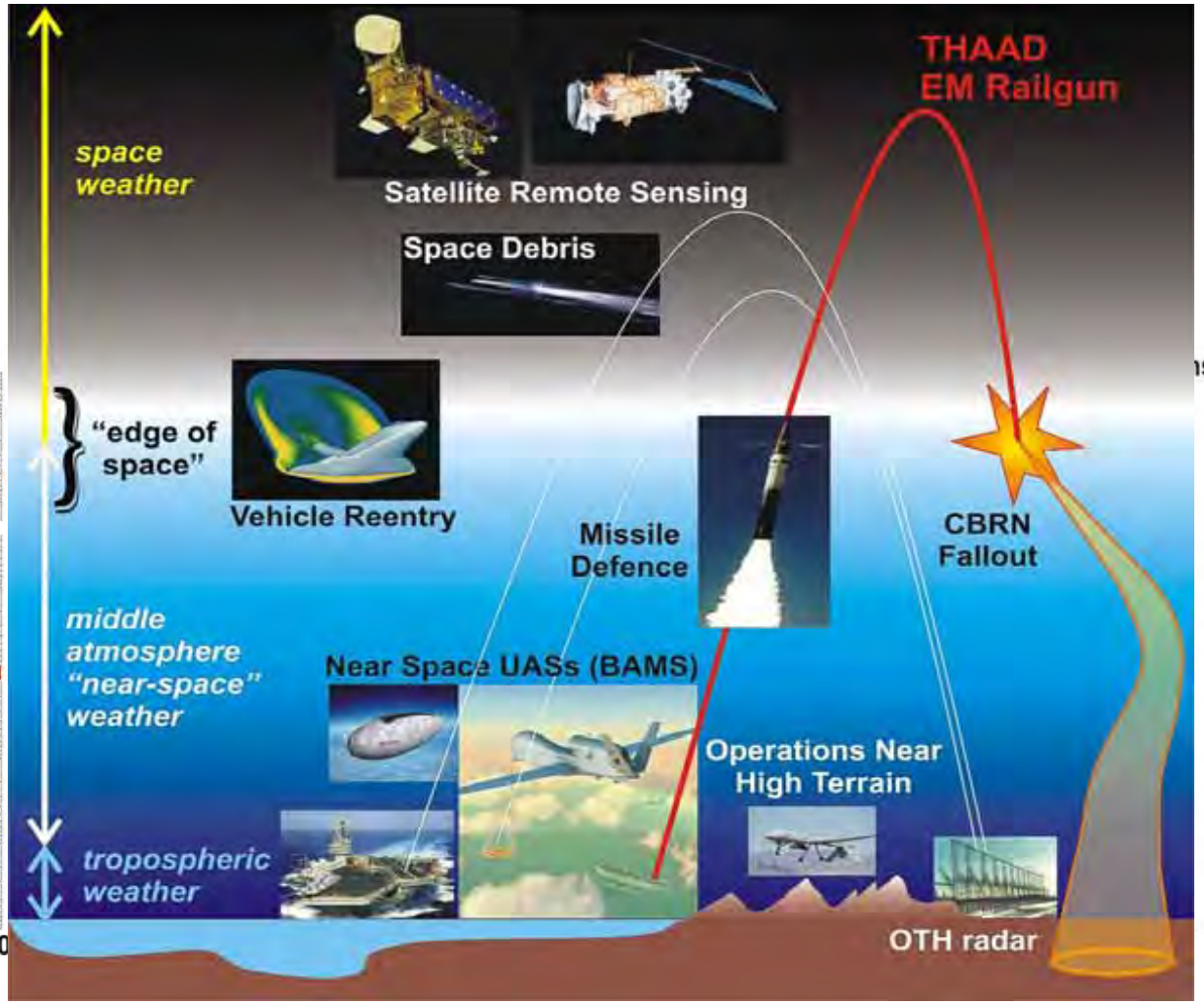
6. Mesospheric Assimilation

7. Validation & Science

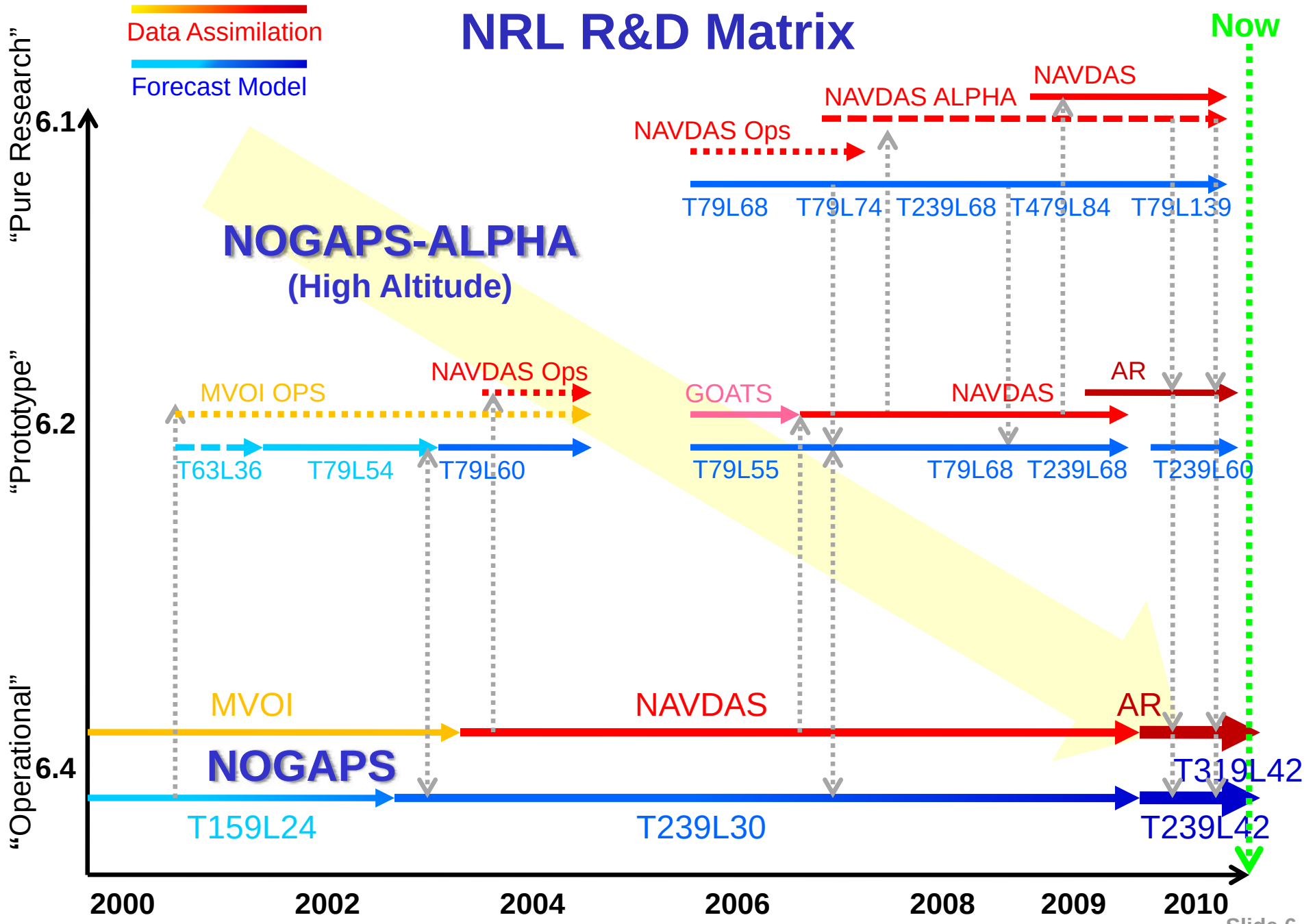
Why NOGAPS-ALPHA? Why Navy? Why Now?

Operational NOGAPS 2000-09





NRL R&D Matrix



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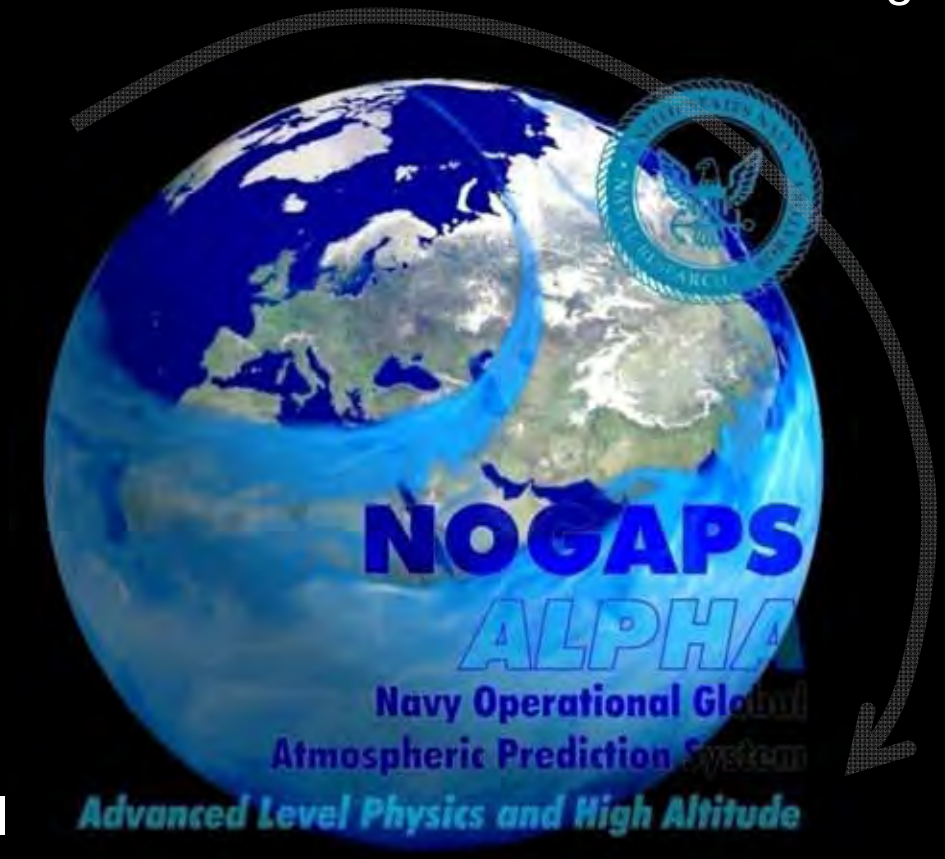

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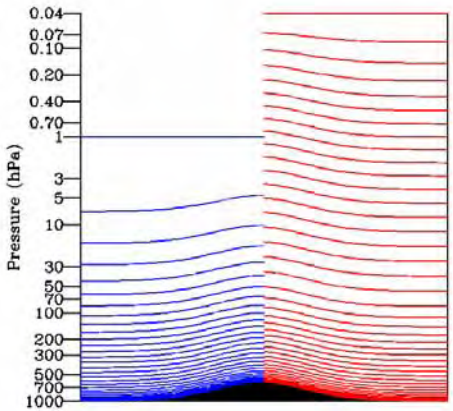
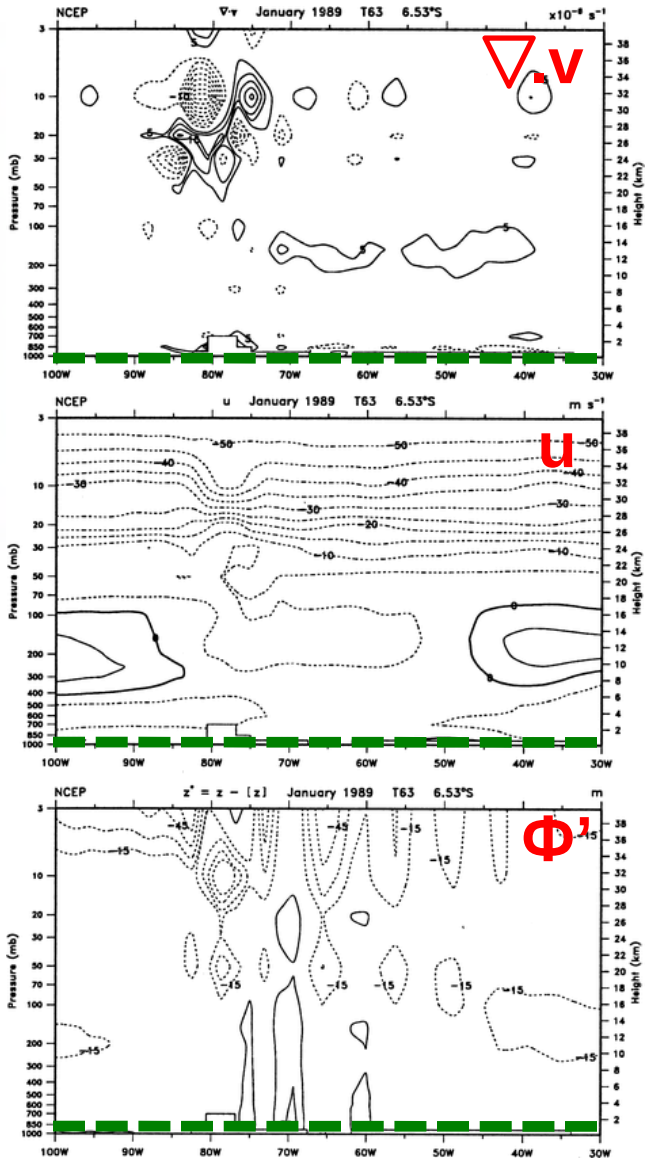
“Pathological Problems” in σ-coordinate Analyses

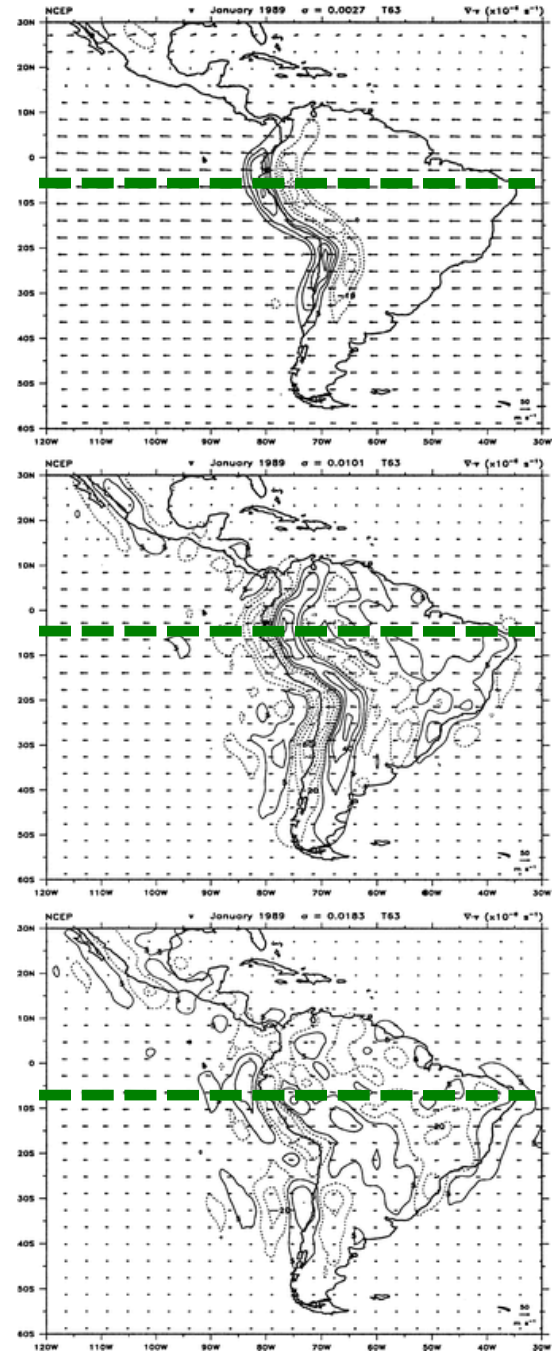
Trenberth and Stepaniak
[*J. Climate*, 2002]



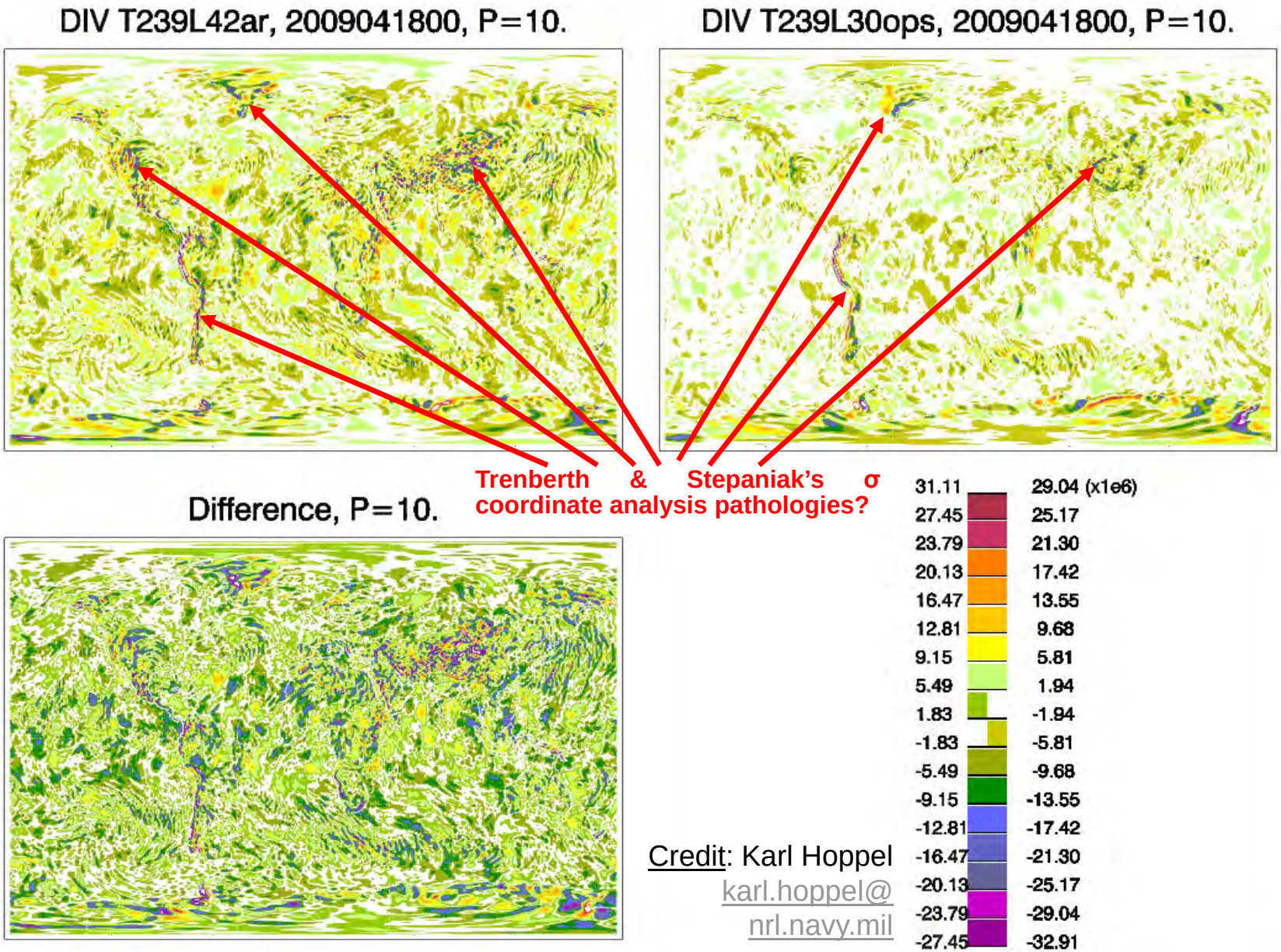
- Stratospheric divergence anomalies aggregate over sharp steep orography as 2ΔZ noise structures
- ascribed to σ-coordinate truncation errors & possible upper boundary condition
- not present in ECMWF hybrid coordinate analyses

→ Suggests transition to hybrid coordinates should remove these anomalies





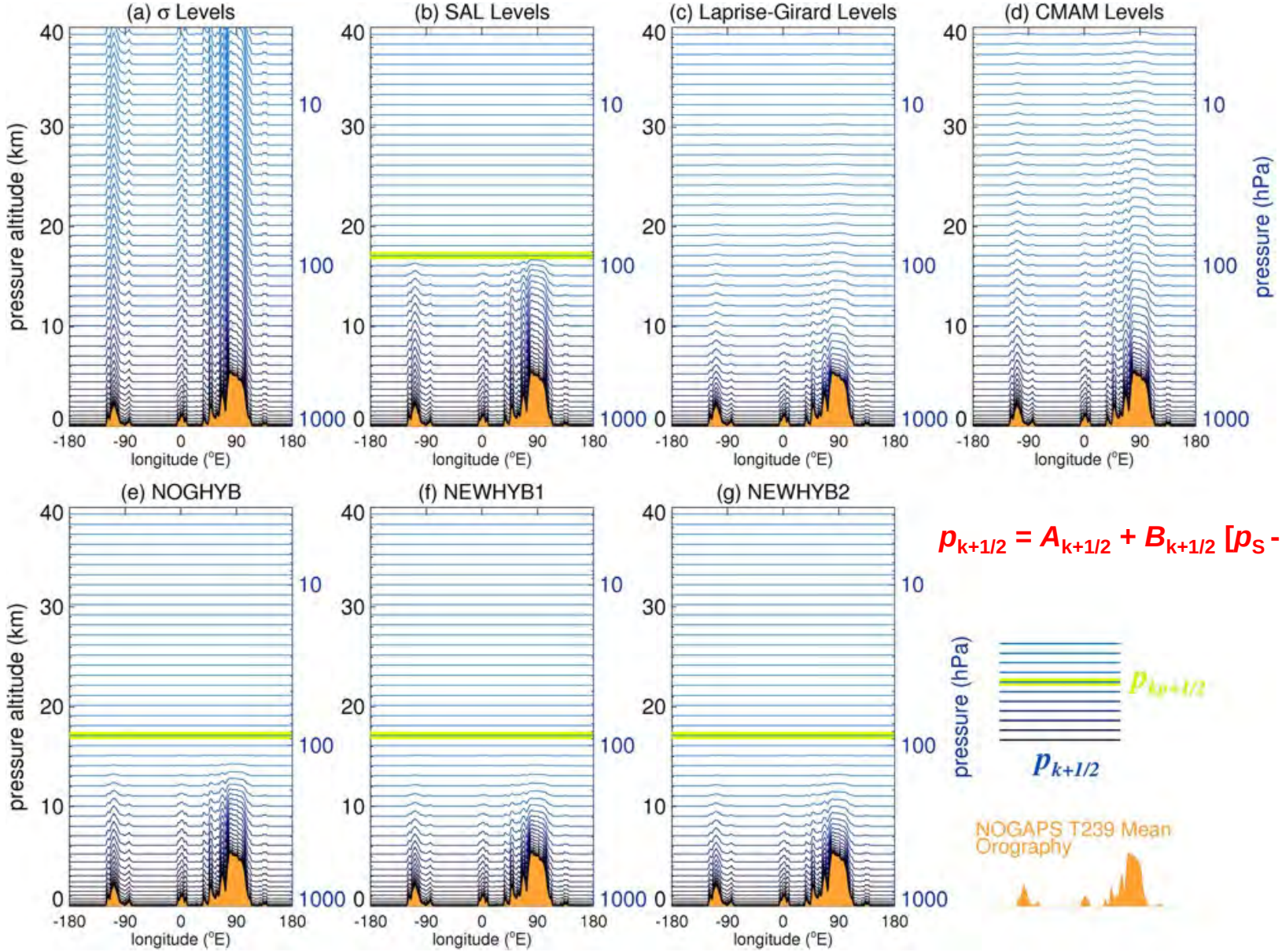
T239L42/L30 Analyzed 10 hPa Divergences



Trenberth & Stepaniak's σ coordinate analysis pathologies?

Credit: Karl Hoppel
karl.hoppel@nrl.navy.mil

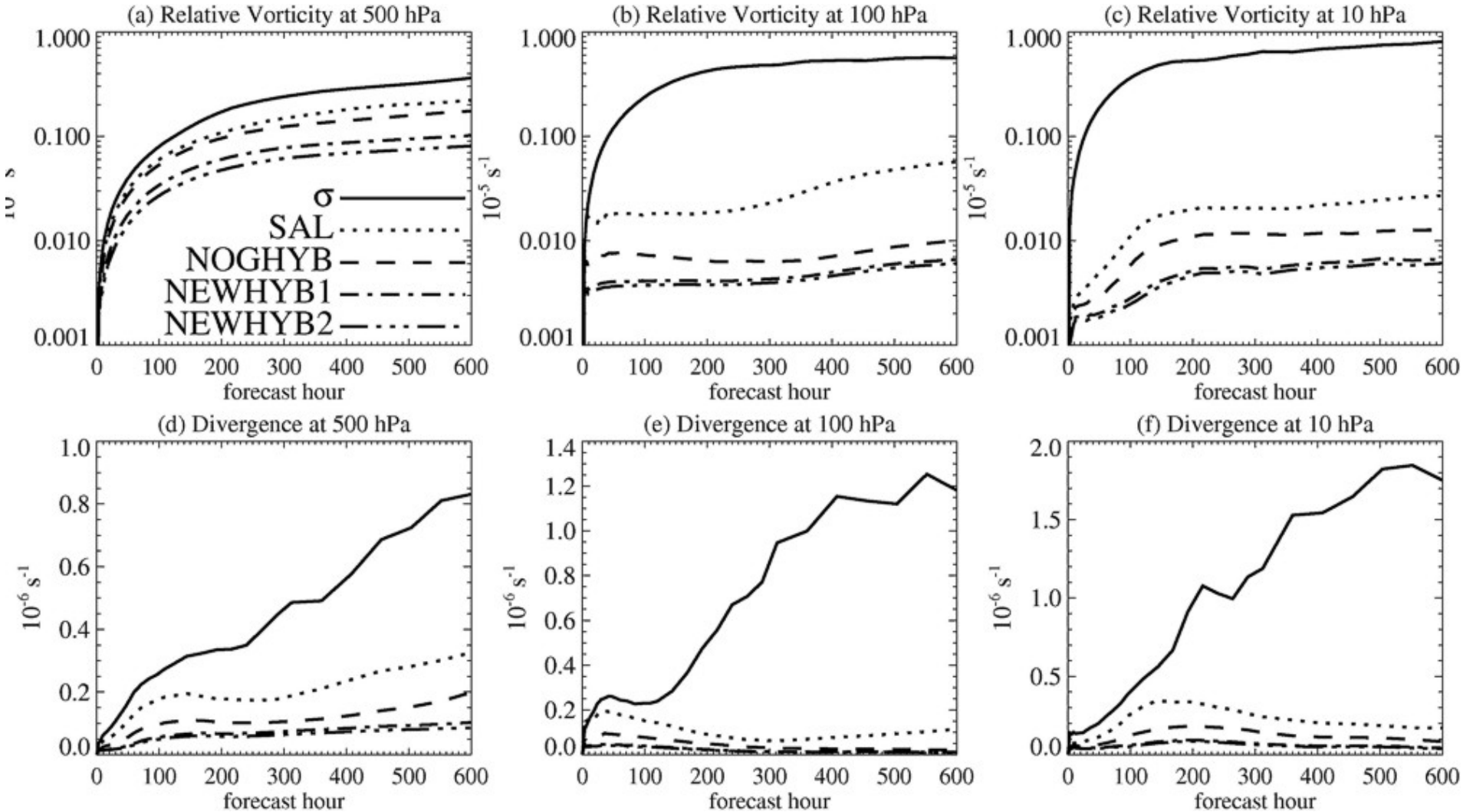
Different Hybrid Coordinates Tested (ALPHA L84)



Vorticity and Divergence Errors in NOGAPS-ALPHA

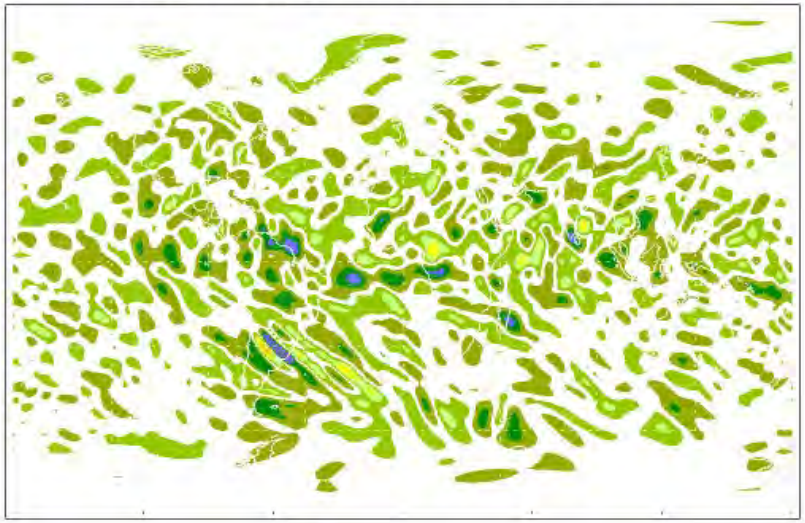
Idealized Static Atmosphere Simulations with Topography

[Eckermann, Mon. Wea. Rev., 137, 224–245, 2009]

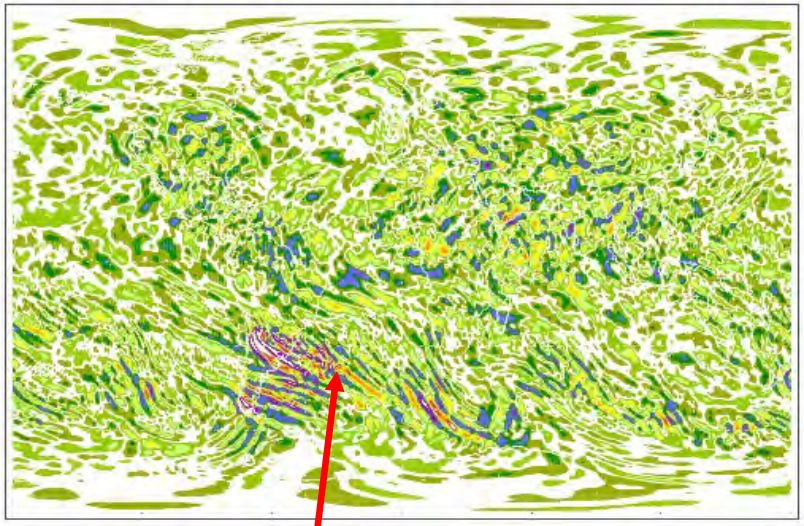


T79/T239L68 Hybrid-coordinate ALPHA Analyses

T79 DIV aim9c, 2007060200, P=10.



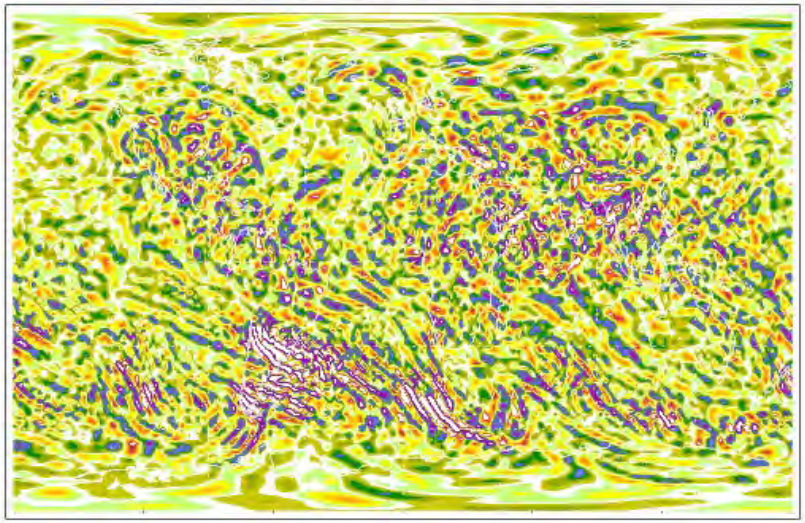
DIV aim9cT239, 2007060200, P=10.

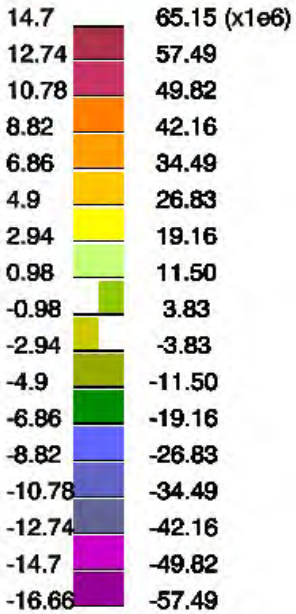


No sign of Trenberth & Stepaniak divergence pathologies

Real resolved gravity waves from Andes

Difference, P=10.





Credit: Karl Hoppel
karl.hoppel@nrl.navy.mil

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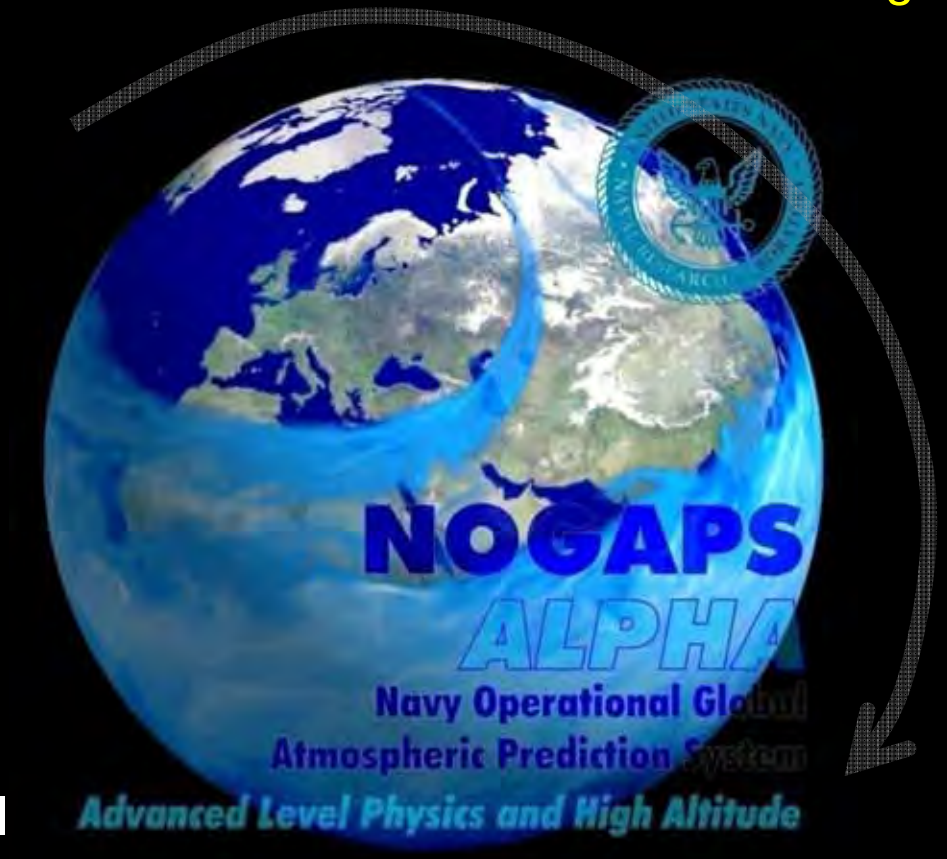

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Gravity-Wave Drag Parameterization is to Stratospheric and Mesospheric NWP what Convection Parameterization is to Tropospheric NWP

"***This problem*** *(of parameterizing unresolved gravity wave drag)* ***hampers middle atmosphere GCM*** *(general circulation model)* ***studies in much the same way that the convective parameterization problem hampers tropospheric GCM studies.***"

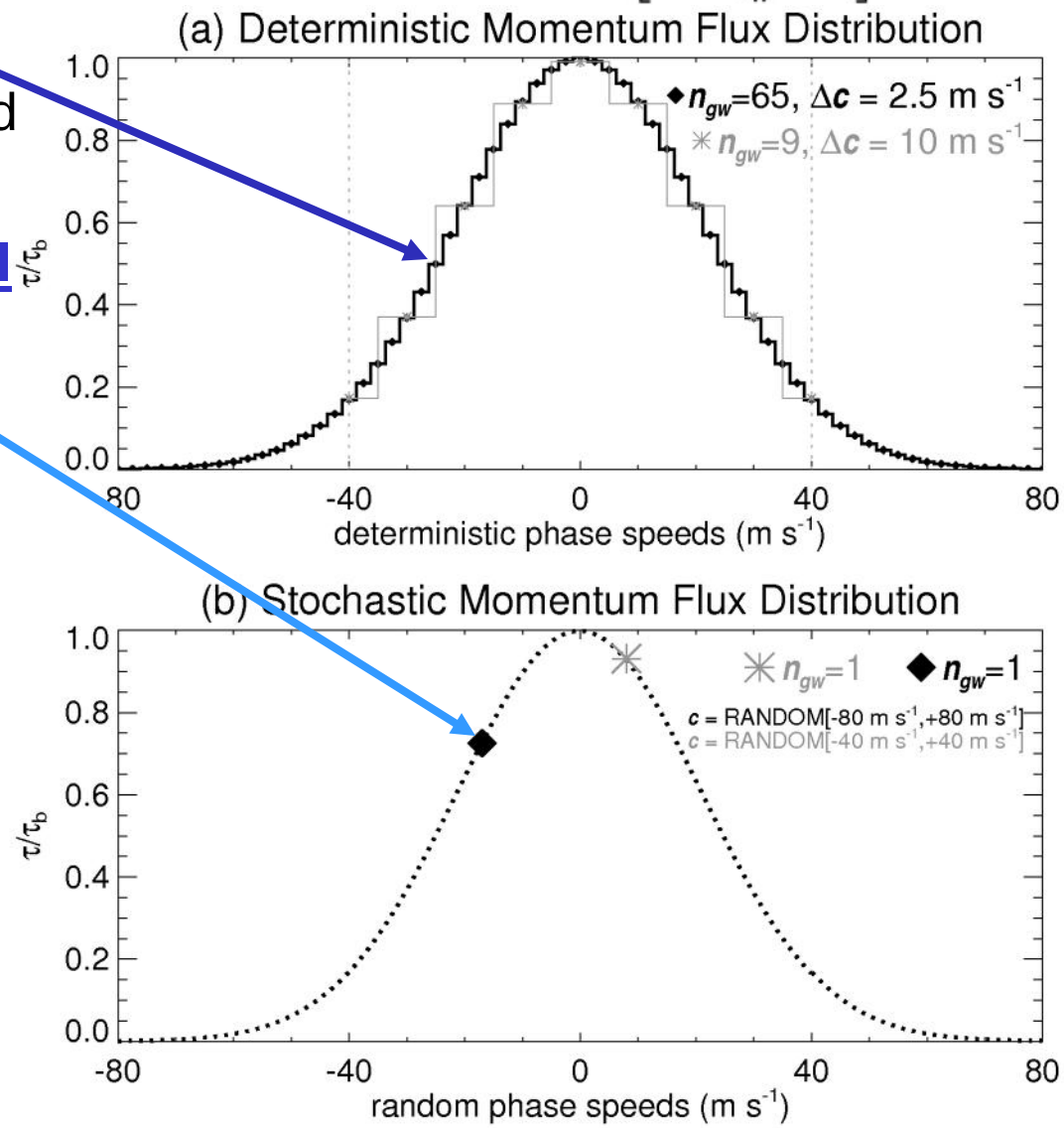
(quote, page 1599 of Shepherd, T. G., The middle atmosphere, *J. Atmos. Sol. Terr. Phys., 62*, 1587–1601, 2000.)

Within the data assimilation context, these parameterizations require extensive tuning to minimize O-F and A-F biases

New Stochastic Version of Nonorographic Gravity Wave Drag "Team Scheme" for NOGAPS-ALPHA

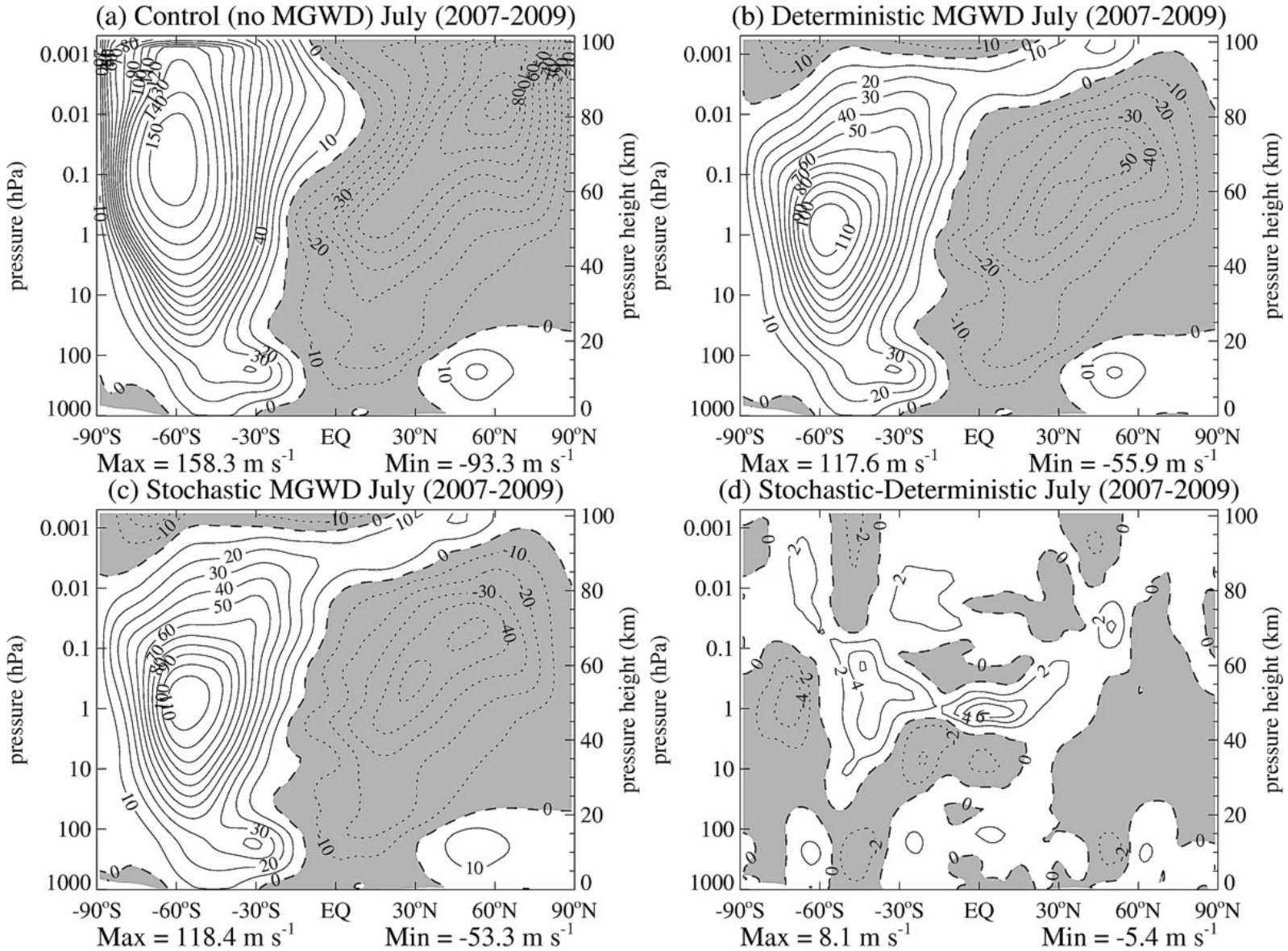
- Current scheme [*Garcia et al*., 2007] launches a 65-wave source spectrum at every grid point and time step
- **Consumes >20-40% of <u>total</u> NOGAPS-ALPHA runtime**
- New scheme launches one wave whose phase speed is assigned randomly in the range –80m/s< *c* < +80m/s
- The source flux Gaussian is progressively mapped out over time/horizontally
- New scheme is *explicitly* stochastic *and* intermittent
- **In theory, 65 times faster!**

$$\tau_{src}(c_j) = \tau_b F(\phi, t) \exp\left[\frac{-(c_j - c_{j=0})^2}{\hat{c}_w^2}\right]$$



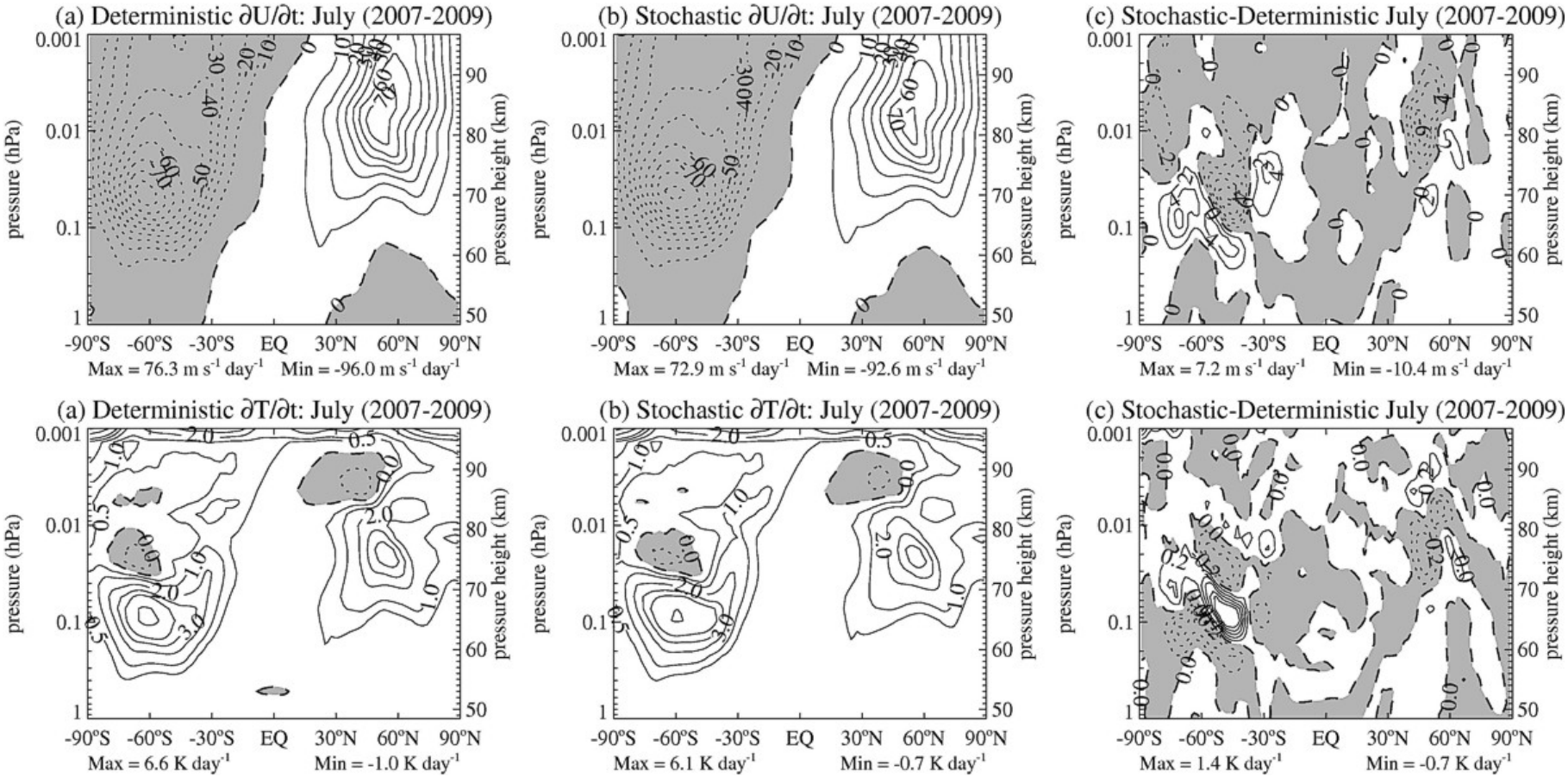
Tests in NOGAPS-ALPHA: 3 Year Nature Run

Zonal-Mean Zonal Winds for July



Tests in NOGAPS-ALPHA: 3 Year Nature Run

Zonal-Mean GW-induced Acceleration and Heating Rates for July



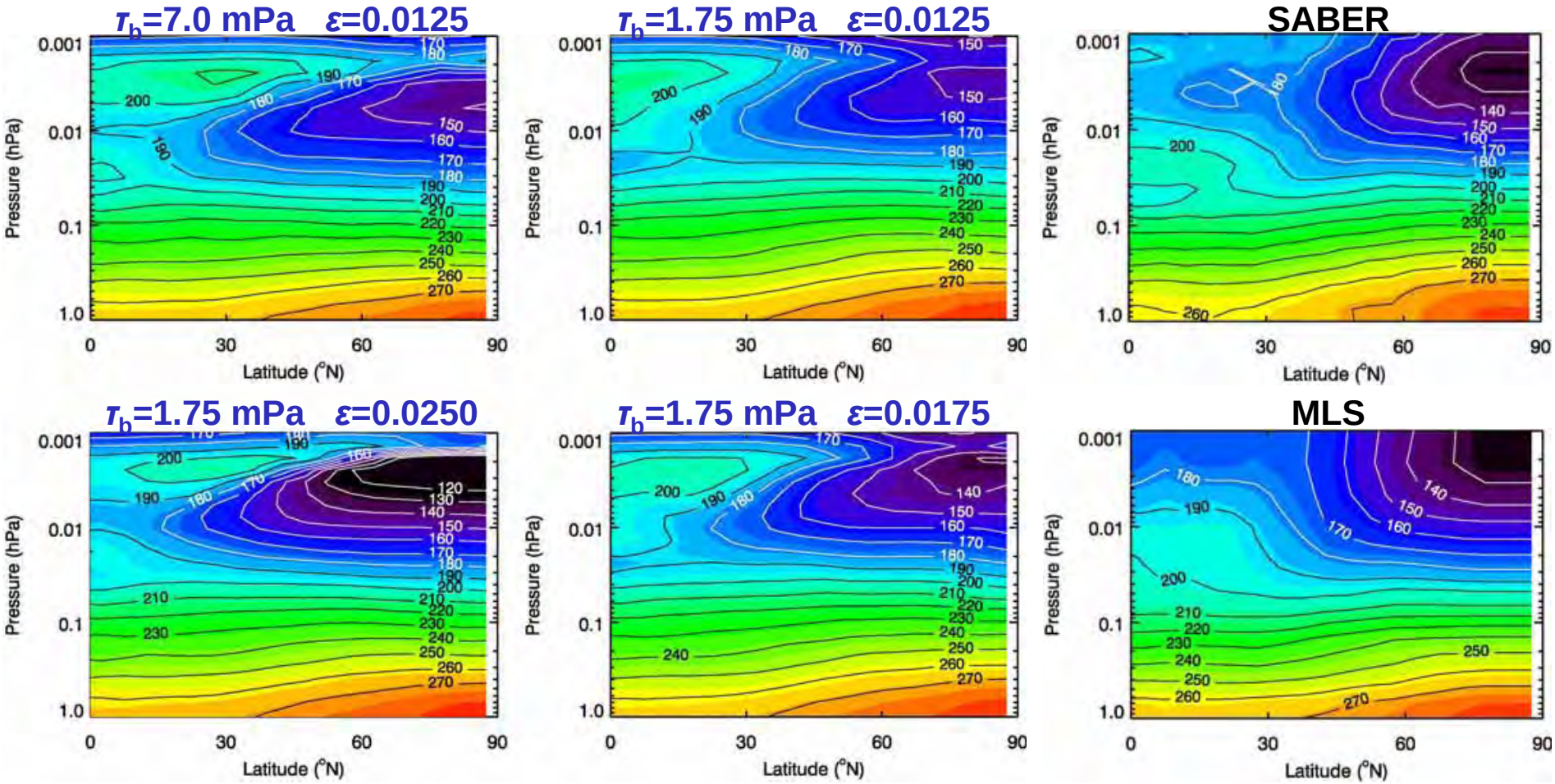
Stochastic 1-wave scheme produces identical climate to deterministic 65-wave scheme but it is between 10-20 times faster computationally in the model.

[Eckermann, S. D., Explicitly stochastic parameterization of nonorographic gravity-wave drag, J. Atmos. Sci., in press, 2011]

GWD Tuning for Mesospheric Data Assimilation

Zonal-Mean Temperatures June 2007

Eckermann, S. D., K. W. Hoppel, L. Coy, J. P. McCormack, D. E. Siskind, K. Nielsen, A. Kochenash, M. H. Stevens, C. R. Englert, and M. Hervig, High-altitude data assimilation system experiments for the northern summer mesosphere season of 2007, *J. Atmos. Sol.-Terr. Phys., 71,* 531-551, 2009.



$$a_{j,k} = -g\epsilon \frac{\partial \tau_{j,k}}{\partial p},$$

$$\tau_{src}(c_j) = \tau_b F(\phi, t) \exp\left[\frac{-(c_j - c_{j=0})^2}{\hat{c}_w^2}\right]$$

$$a_k^{tot} = \sum_{j=1}^{n_{gw}} a_{j,k},$$

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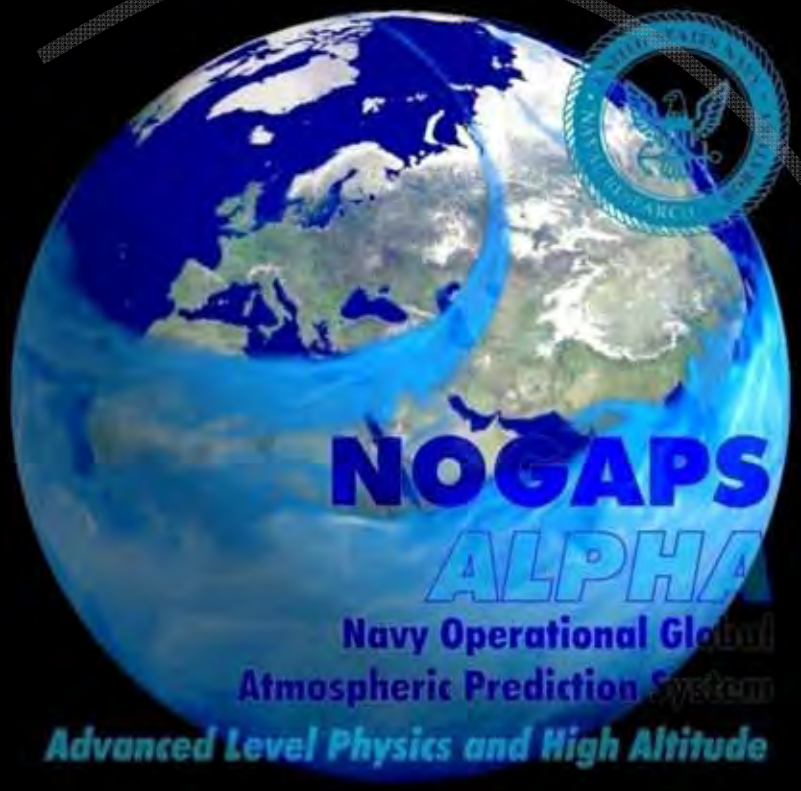

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NRL's Fast Gas-Phase Ozone Photochemistry Scheme

CHEM2D-OPP
Parameterized Ozone Photochemistry for Weather & Climate Models

McCormack, J. P., S. D. Eckermann, D. E. Siskind, and T. J. McGee, CHEM2D-OPP: A new linearized gas-phase ozone photochemistry parameterization for high-altitude NWP and climate models, *Atmos. Chem. Phys.*, *6*, 4943-4972, 2006.

1. Which Parameters Most Strongly Influence Ozone Photochemical Production and Loss (P-L)?

(a) Local Ozone Mixing Ratio *f*:
(b) Local Temperatures *T*:
(c) Overhead Vertical Column Density of Ozone c_{O3}:

} Homogeneous (Standard Gas Phase) Chemistry

(d) Heterogeneous (Ozone Loss) Chemistry

$$\frac{df}{dt} = (P-L)[f, T, c_{O_3}]$$

2. Express this Functional Dependence of Ozone Production/Loss as Truncated Taylor Series….

$$\frac{df}{dt} = (P-L)^o + \left.\frac{\partial(P-L)}{\partial f}\right|_o (f-f^o) + \left.\frac{\partial(P-L)}{\partial T}\right|_o (T-T^o) + \left.\frac{\partial(P-L)}{\partial c_{O_3}}\right|_o (c-c^o_{O_3})$$

Photochemistry Parameters (*y,z,t* Lookup Tables)

1. Mean/Equilibrium Production-Loss $(P\text{-}L)_0$
2. Photochemical Relaxational Timescale $\tau = -[d(P\text{-}L)/df]_0^{-1}$
3. Temperature Perturbation Coefficient $[d(P\text{-}L)/dT]_0$
4. Overhead Column O_3 Perturbation Coefficient $[d(P\text{-}L)/dc]_0$

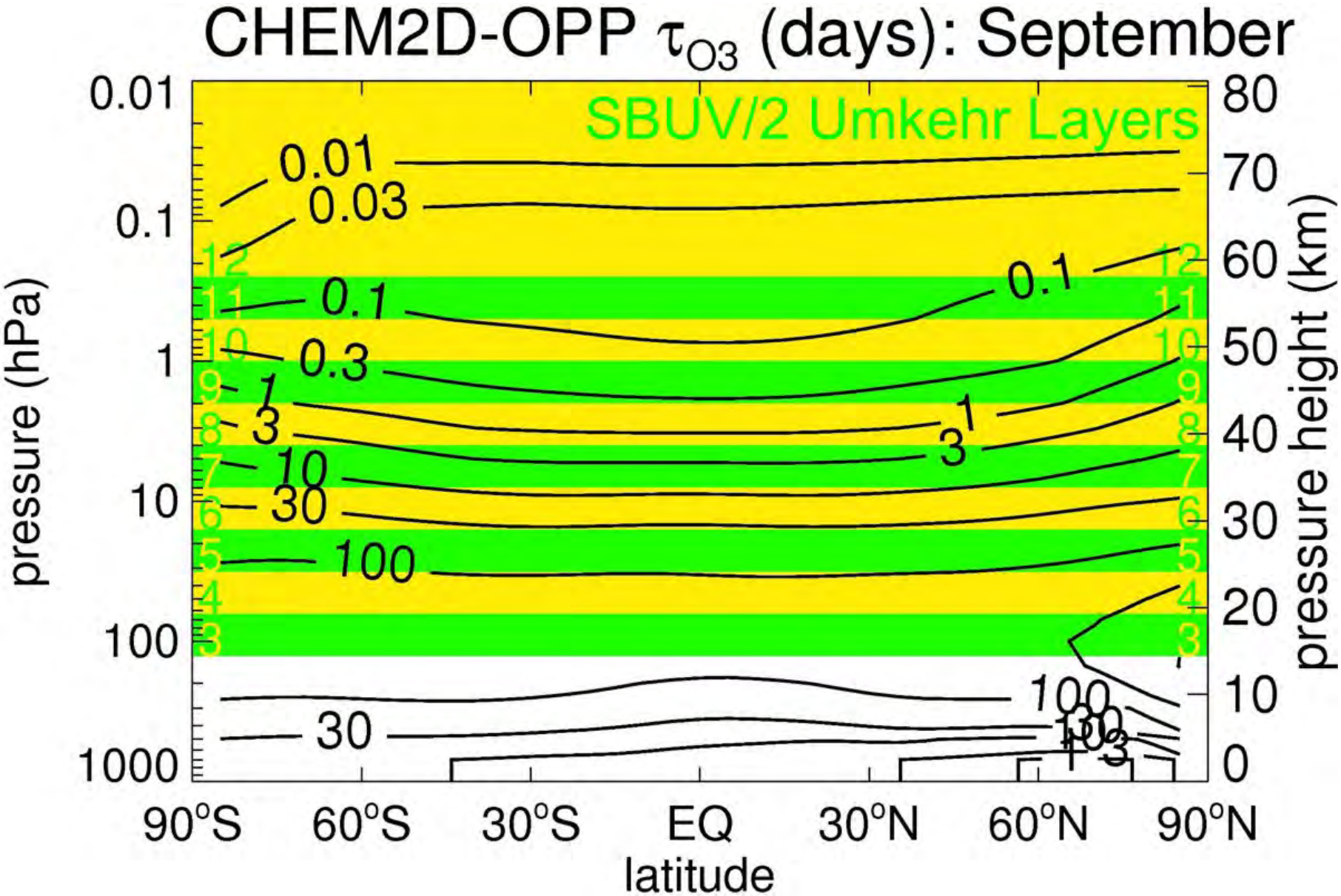
Climatological Fields (*y,z,t* Lookup Tables)

1. Ozone $f_0(y,z,t)$
2. Temperature $T_0(y,z,t)$
3. Column O_3 $c_{03}(y,z,t)$

NOGAPS-ALPHA Fields

1. Ozone Mixing Ratio, *f*
2. Temperature, *T*
3. Overhead Column O_3, *c*

3. These 4 photochemical perturbation coefficients are specified using diurnal, zonal and monthly averaged output from (f,T,c_{O3}) perturbation experiments using full-photochemistry 2D global chemical-dynamical models. The 3 climatological fields must be carefully chosen to match the ozone data being assimilated.



Photochemical Relaxation Timescale $\tau_{O3} = -[d(P-L)/df]_0^{-1}$

"Why Does Stratospheric Ozone Photochemistry Make Ozone Assimilations Worse?"

(quote), Dr. Steven Pawson, NASA Goddard Space Flight Center, Ozone Assimilation Mini-Workshop, Naval Research Laboratory, 10 May, 2005)

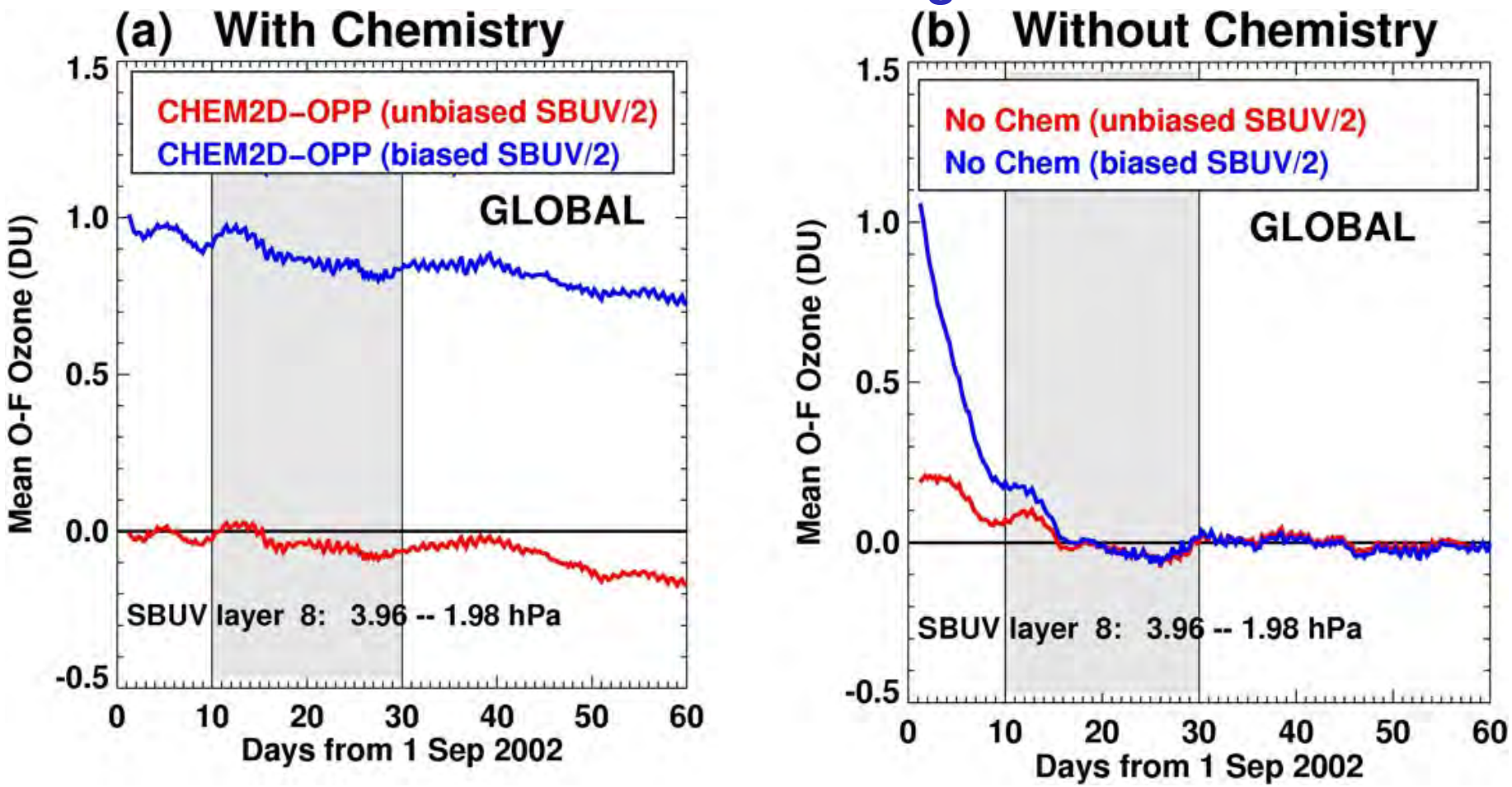
Paraphrase: Why do models with parameterized ozone chemistry produce large mean ozone O-Fs, whereas models without ozone chemistry do not?

This paradox was solved/clarified through NOGAPS-ALPHA assimilation experiments performed with & without photochemistry and real biases in SBUV/2 ozone [Coy et al., *Atmos. Chem. Phys*., 7, 2917-2935, 2007]

Resolution:

- Mean ozone O-Fs are always small in models *without* chemistry since the model simply advects the initial ozone field, even when that ozone field is biased
- Ozone photochemistry, on the other hand, reduces (enhances) ozone mixing ratios that are artificially biased high (low) in the model, leading to large mean ozone O-Fs
- Our research reveals systematic mean drifts with time (biases) in operational SBUV/2 ozone observations that lead to mean O-Fs in assimilation systems with chemistry
- **The large mean ozone O-Fs implicate the "O", not the "F" as had been assumed**
- Model photochemistry is in fact effective in real-time detection and correction of drifting SBUV/2 biases via continuous monitoring of mean ozone O-Fs in systems with chemistry.
- Model photochemistry also significantly reduces the standard deviation of the ozone O-Fs

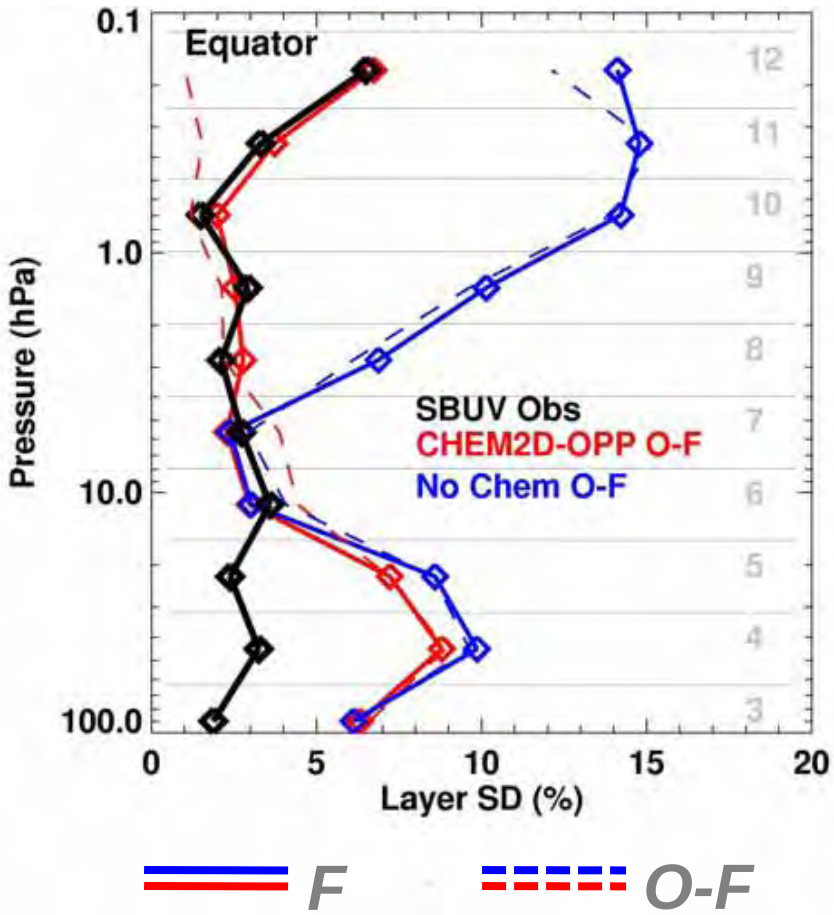
Role of Model Photochemistry in Real-Time Bias Detection and Correction Using O-Fs

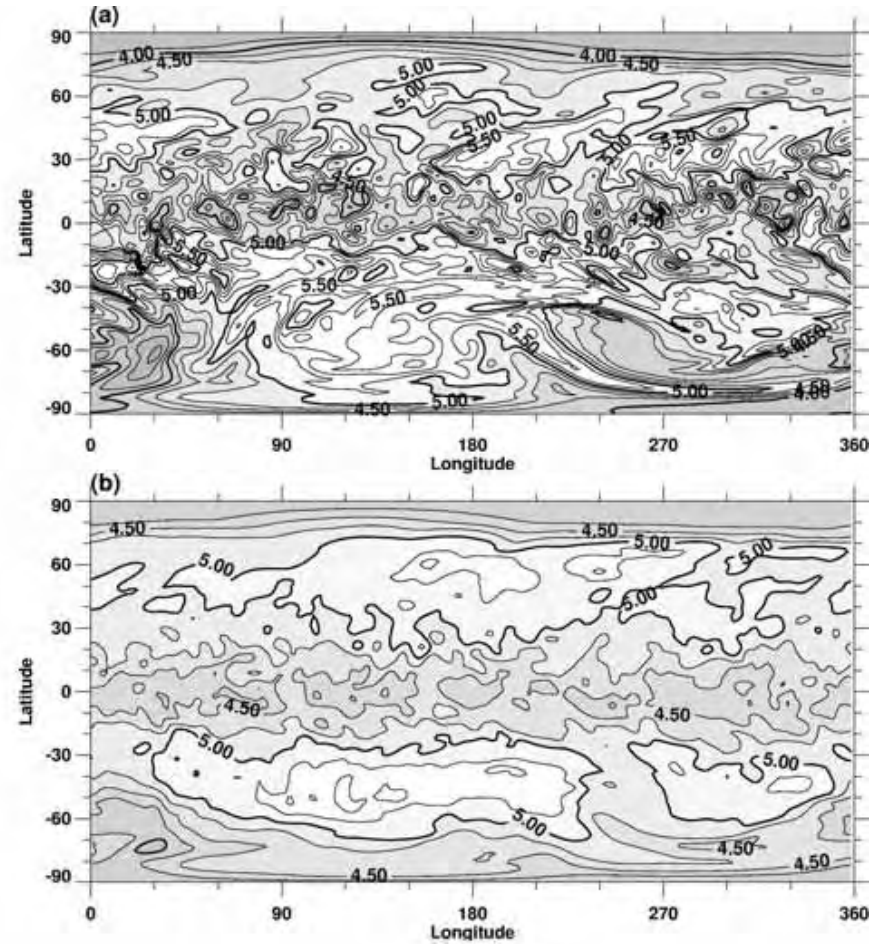


Coy, L., D. R. Allen, S. D. Eckermann, J. P. McCormack, I. Stajner, and T. F. Hogan (2007), Effects of model chemistry and data biases on stratospheric ozone assimilation, *Atmos. Chem. Phys.*, *7*, 2917-2935.

$$\frac{df}{dt} = (P-L)^o + \boxed{\left.\frac{\partial(P-L)}{\partial f}\right|_o (f-f^o)} + \left.\frac{\partial(P-L)}{\partial T}\right|_o (T-T^o) + \left.\frac{\partial(P-L)}{\partial c_{O_3}}\right|_o (c-c^o_{O_3})$$

Chemistry Reduces Ozone O-F Variance Caused by Forecast Model Noise





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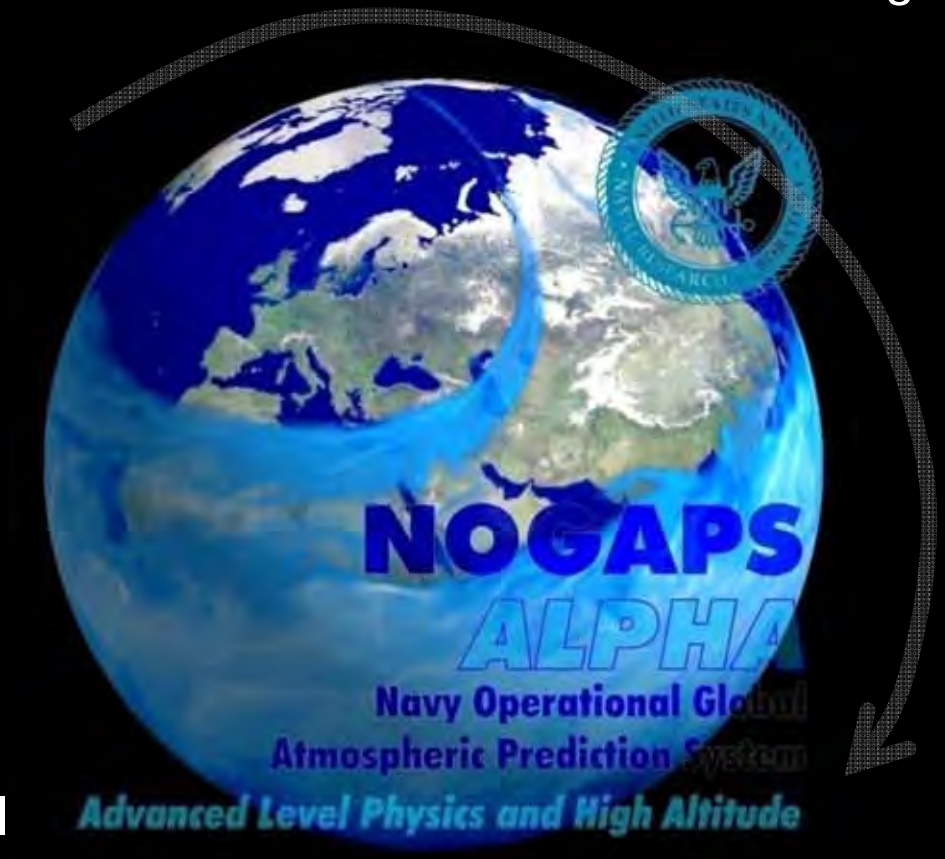

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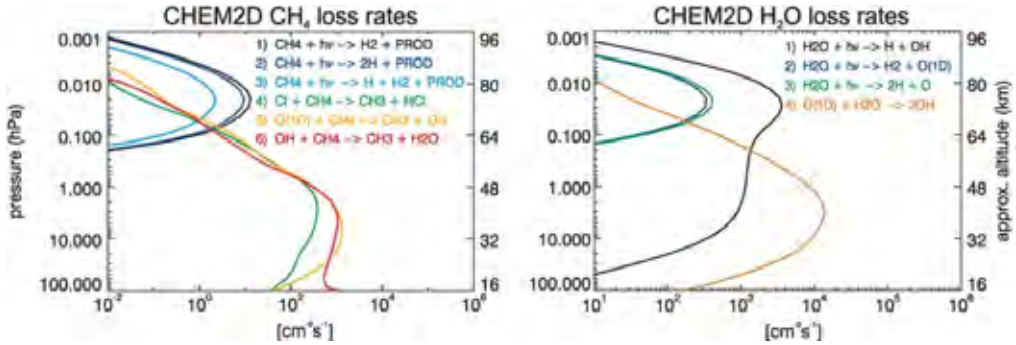
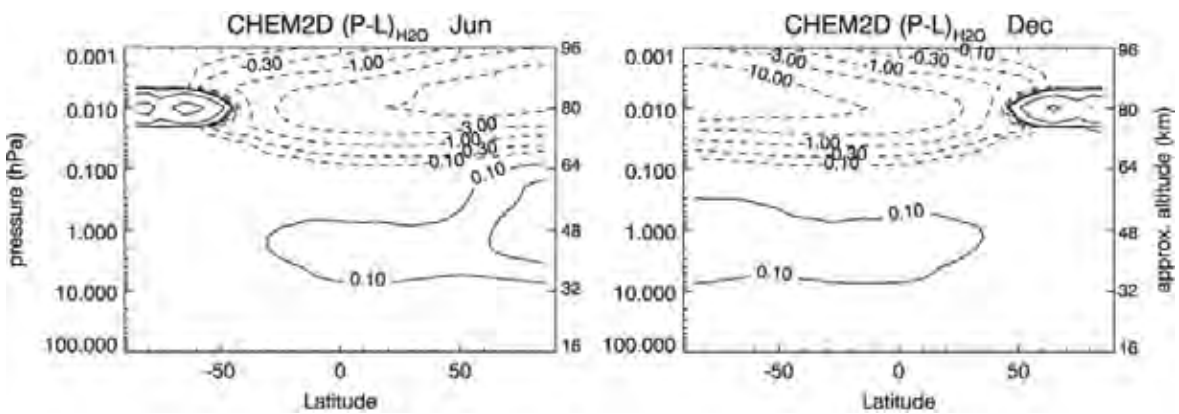
Stratospheric Humidity Assimilation

- Long history of problems in NWP systems due to the large and sharp gradient between very wet and very dry values across the tropopause (e.g., Thornton et al., *The ASSET intercomparison of stratosphere and lower mesosphere humidity analyses, Atmos. Chem. Phys., 9*, 995-1016, 2009)
- NOGAPS-ALPHA humidity analyses were no exception. Stratospheric humidity anomalies were removed via an exhaustive series of incremental fixes: e.g.,
  1. Correcting vertical extrapolations based on analyzed dew point depressions
  2. Correcting tropospheric parameterizations that produced spurious stratospheric rain/ice
  3. Identifying wet analysis artifacts (e.g., from outlier radiosonde stations) that evaded DAS QC
  4. Inconsistent/variable use of “floor values” of humidity and spectral “hole filling” algorithms
  5. **Inclusion of new NRL parameterization of stratospheric and mesospheric water vapor photochemistry** (McCormack et al. 2008)
  6. **Direct assimilation of accurate limb measurements of water vapor from the Microwave Limb Sounder (NASA Aura) throughout the stratosphere and mesosphere**
  7. Careful tuning of observational errors and background error covariances (Thornton et al. 2009)
- NOGAPS-ALPHA analyzed stratospheric humidities now show no major anomalies, allowing *ad hoc* stratospheric humidity “fixers” in the forecast model to be removed.

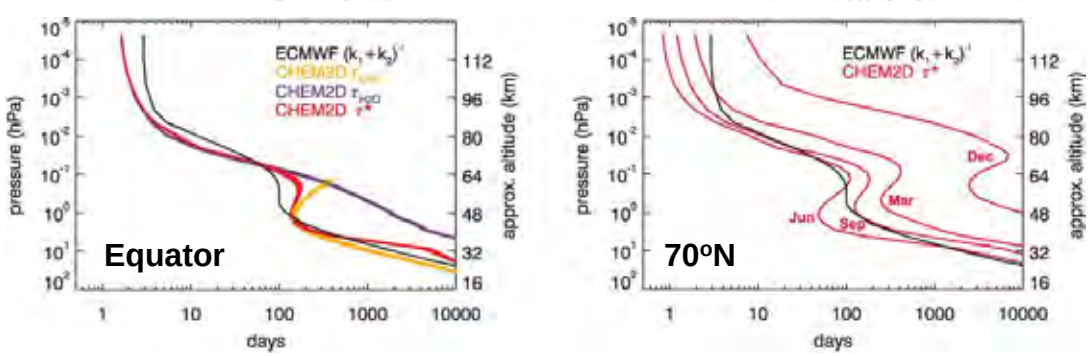
NRL Water Vapor Photochemistry Parameterization



$$\frac{\partial r(\lambda,\phi,p,t)}{\partial t} = (P-L)^o_{\mathrm{H2O}} + \left.\frac{\partial (P-L)_{\mathrm{H2O}}}{\partial r}\right|_o (r-r^o)$$



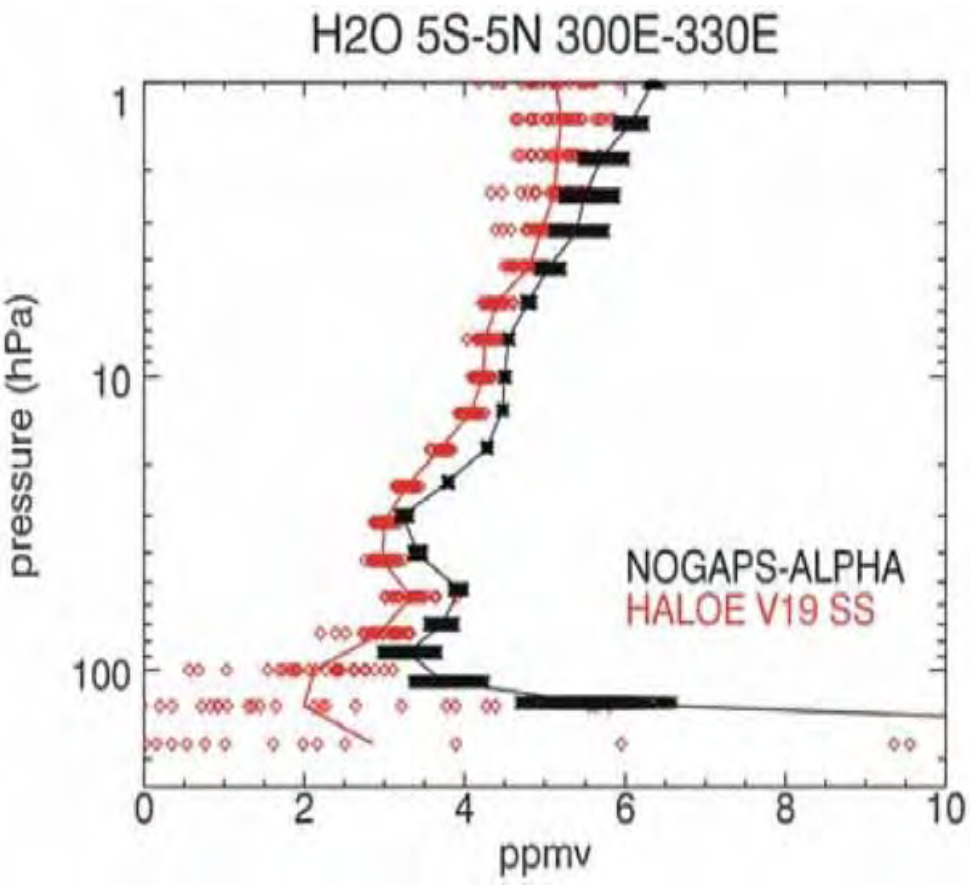
$$(P\text{-}L)_o$$

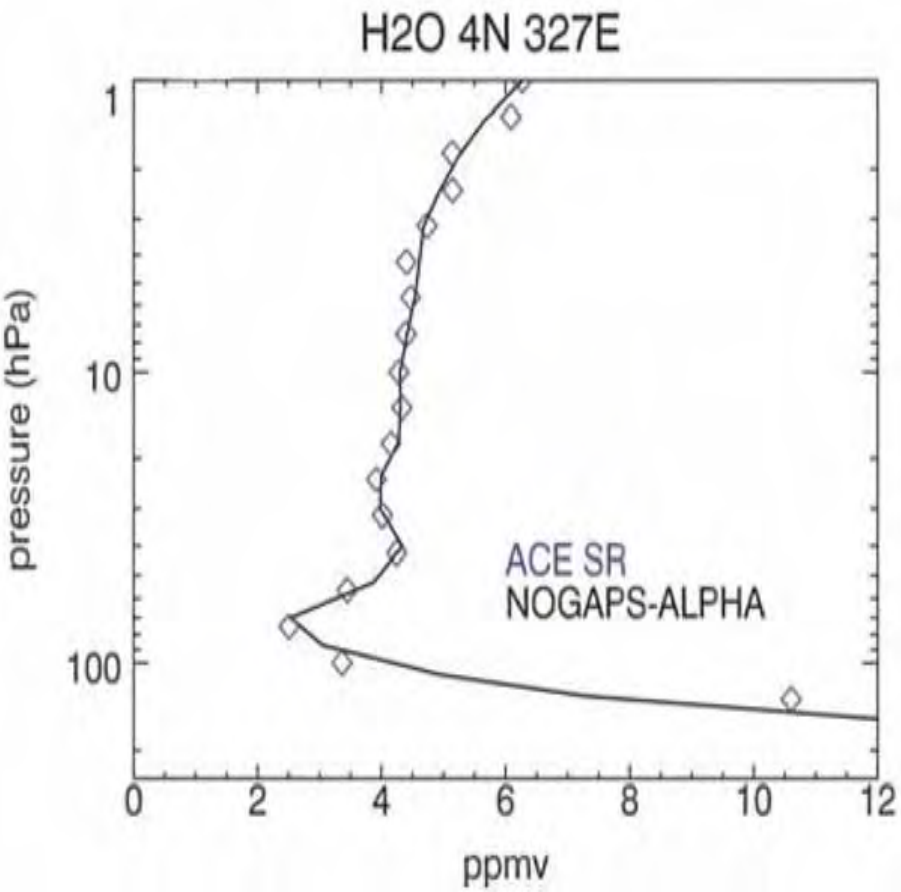


$$\frac{\partial (P-L)^o_{\mathrm{H_2O}}}{\partial r}\Big|_o = -\left(\tau^*\right)^{-1}$$

McCormack, J. P., K. W. Hoppel, and D. E. Siskind (2008), Parameterization of middle atmospheric water vapor photochemistry for high-altitude NWP and data assimilation, *Atmos. Chem. Phys., 8*, 7519-7532.

NOGAPS-ALPHA Moisture Analysis: Validation Against HALOE and ACE Satellite Data





Credit: John McCormack
john.mccormack@nrl.navy.mil

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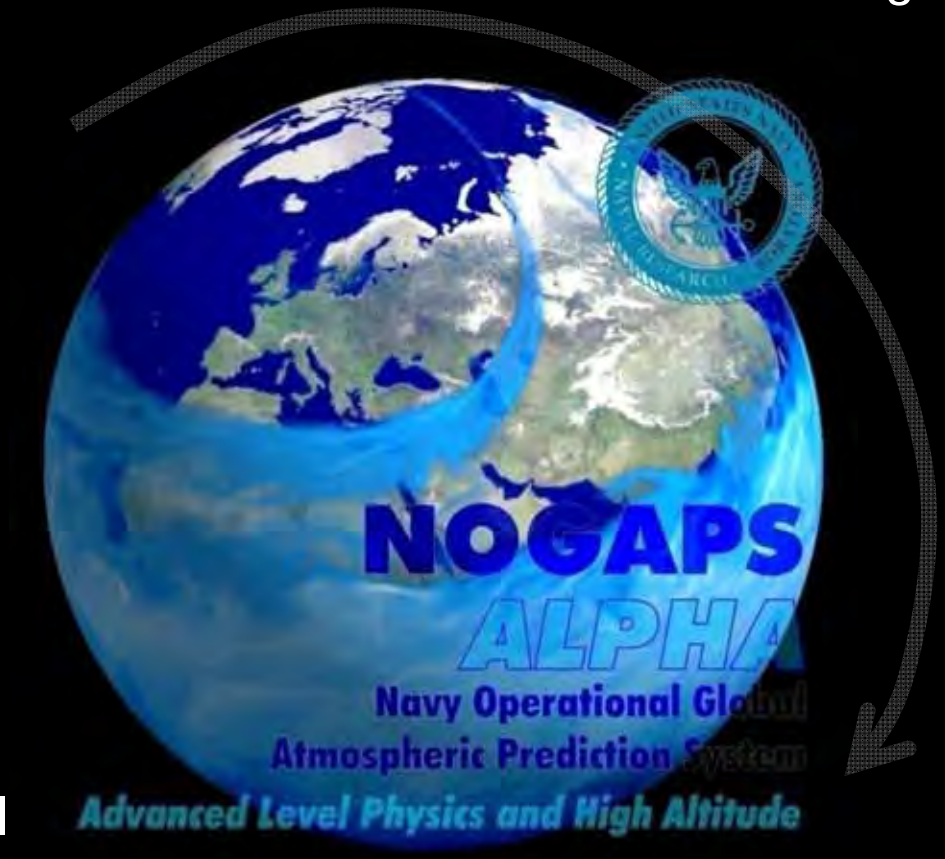
3. Nonorographic Gravity Wave Drag

1. Motivation & R&D History



4. Ozone Assimilation

9. Summary & Outlook

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8. Operational Transitions

6. Mesospheric Assimilation

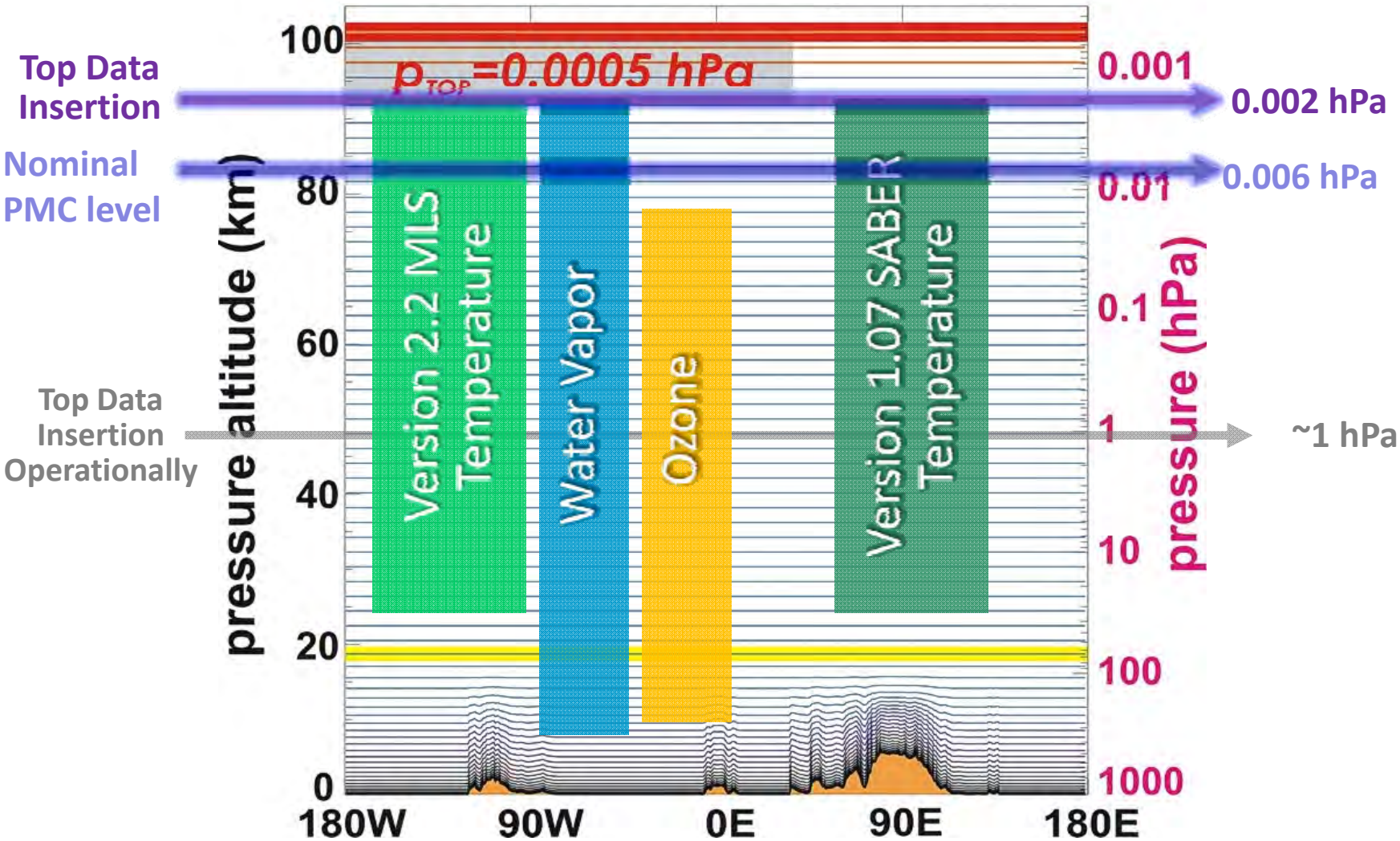
7. Validation and Science

NOGAPS-ALPHA

Navy Operational Global Atmospheric Prediction System (DoD NWP System)

Advanced-Level Physics & High Altitude NWP Prototype

NAVDAS: NRL Atmospheric Variational Data Assimilation System (3DVAR)



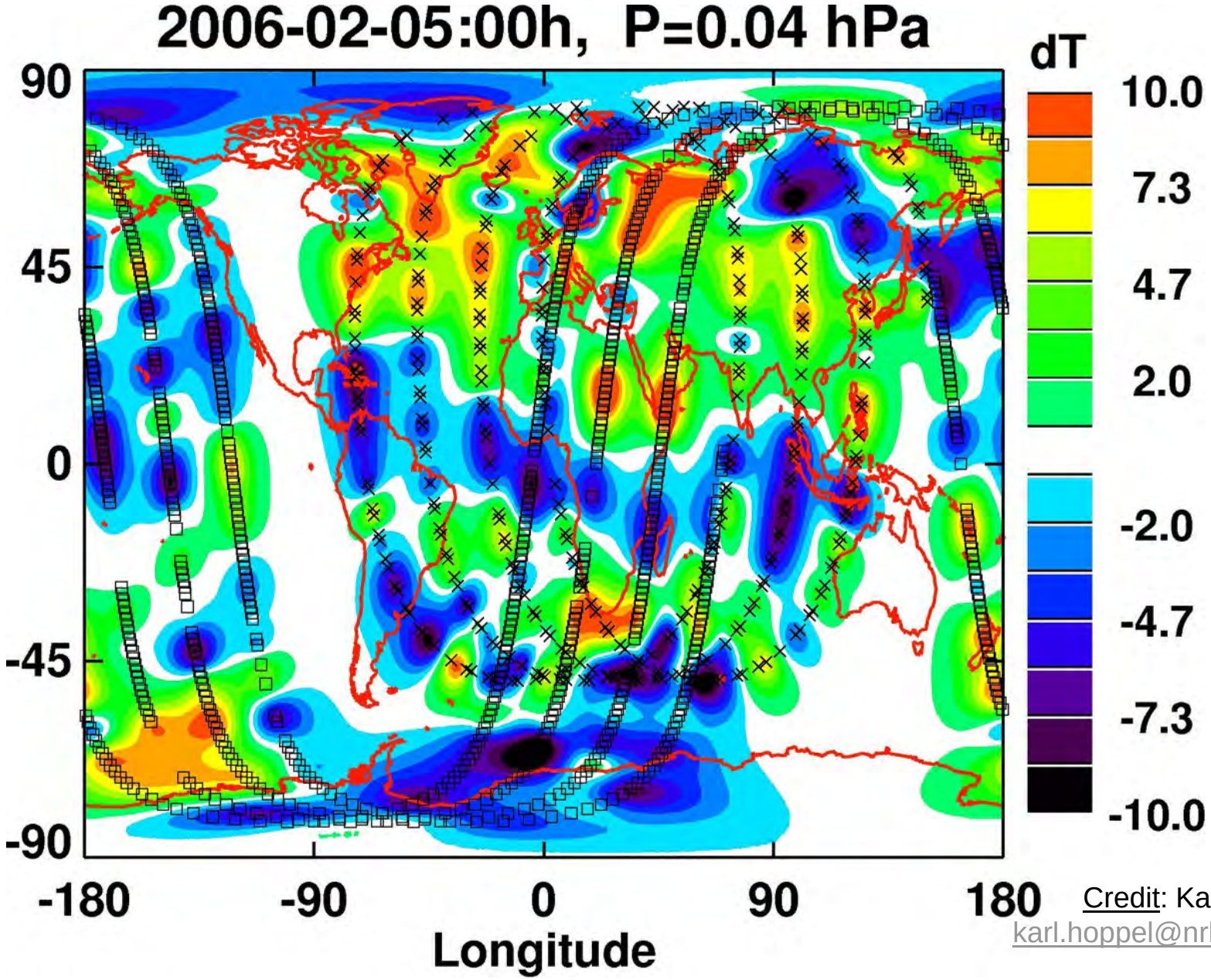
“Production Run:” Practical Assimilation Issues

- NOGAPS-ALPHA used NAVDAS (3DVAR-FGAT, T79L68) with full complement of archived operational channels plus these extra NASA research observations
- Assimilate retrieved limb temperature profiles (fast RT codes lack sufficient physics [e.g., non-LTE] for accurate assimilation of mesospheric thermal microwave or infrared limb radiances)
- Univariate assimilation of version 2.2 MLS ozone and water vapor limb profiles (with chemistry)
- SABER/MLS instrument validation papers defined observational errors and spatial correlation scales, the latter imposed via 2nd order autoregression (SOAR)
- Latest SABER V1.07 retrievals important: inclusion in retrieval of vibrational exchange between CO_2 isotopes substantially improved temperatures at the summer mesopause [*Remsberg et al*., 2008]
- Global-mean SABER-MLS temperature bias calculated and used to correct an ~2 K SABER warm bias at altitudes below 2.7 hPa [*Remsberg et al.,* 2008]
- At higher altitudes remove structured stratopause bias and systematic mesospheric cold bias based on MLS validation study of *Schwartz et al*. [2008]
- Perform 3-point along-track smoothing of MLS H_2O at p<0.02 hPa to beat down excessive point measurement errors at these uppermost heights [*Lambert et al*., 2007]
- SABER yaw cycle yields periodic “denial of data” to one hemisphere
- NNMI of increments needed for better tidal and vertical velocity assimilation

For more details, see…

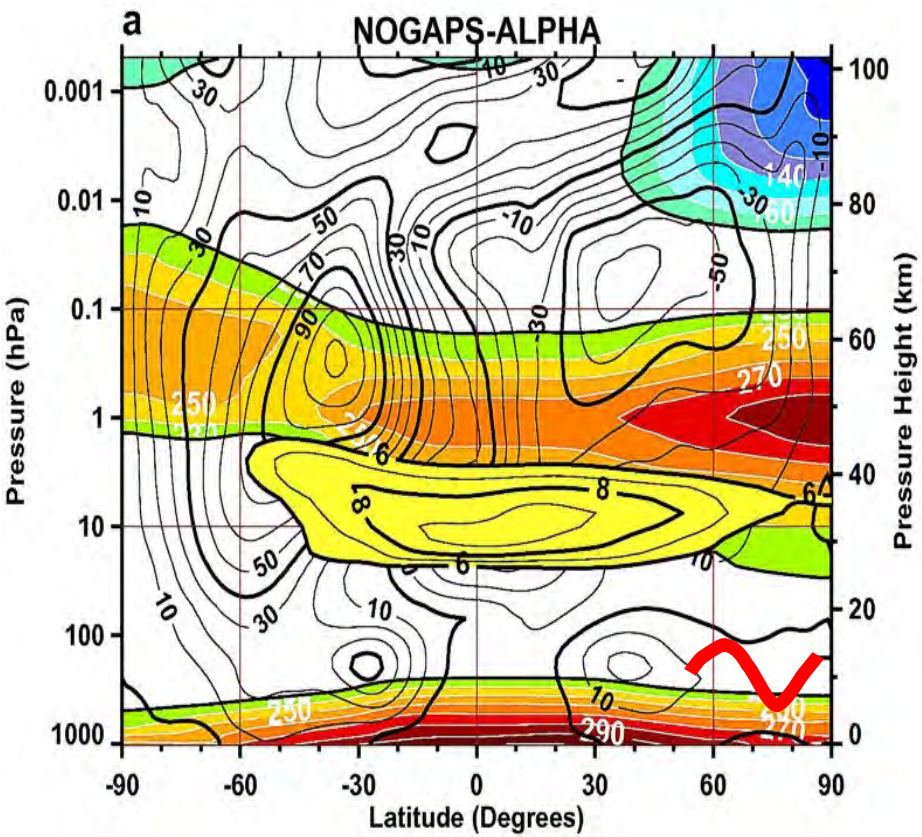
Eckermann, S. D., K. W. Hoppel, L. Coy, J. P. McCormack, D. E. Siskind, K. Nielsen, A. Kochenash, M. H. Stevens, C. R. Englert, and M. Hervig, High-altitude data assimilation system experiments for the northern summer mesosphere season of 2007, *J. Atmos. Sol.-Terr. Phys., 71,* 531-551, 2009.

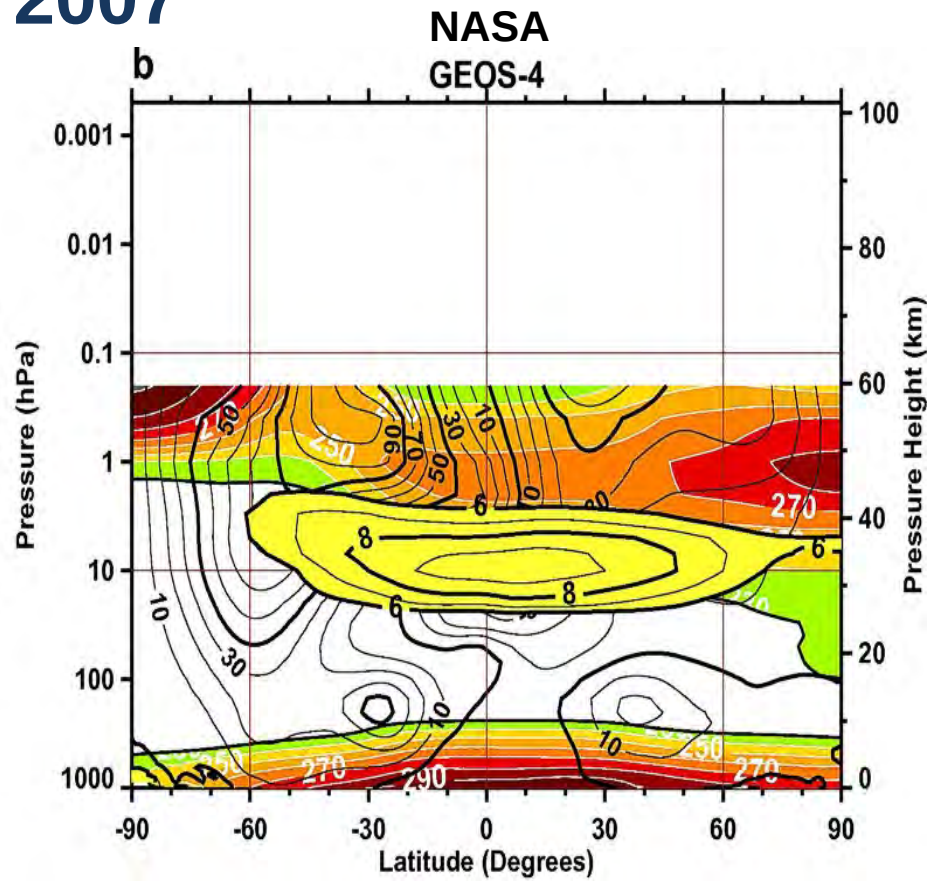
Mesospheric Temperature Corrections (x_a-x_b)



Credit: Karl Hoppel
karl.hoppel@nrl.navy.mil

NOGAPS-ALPHA vs. NASA GEOS-4 Analysis June 2007





Ozone (ppmv)

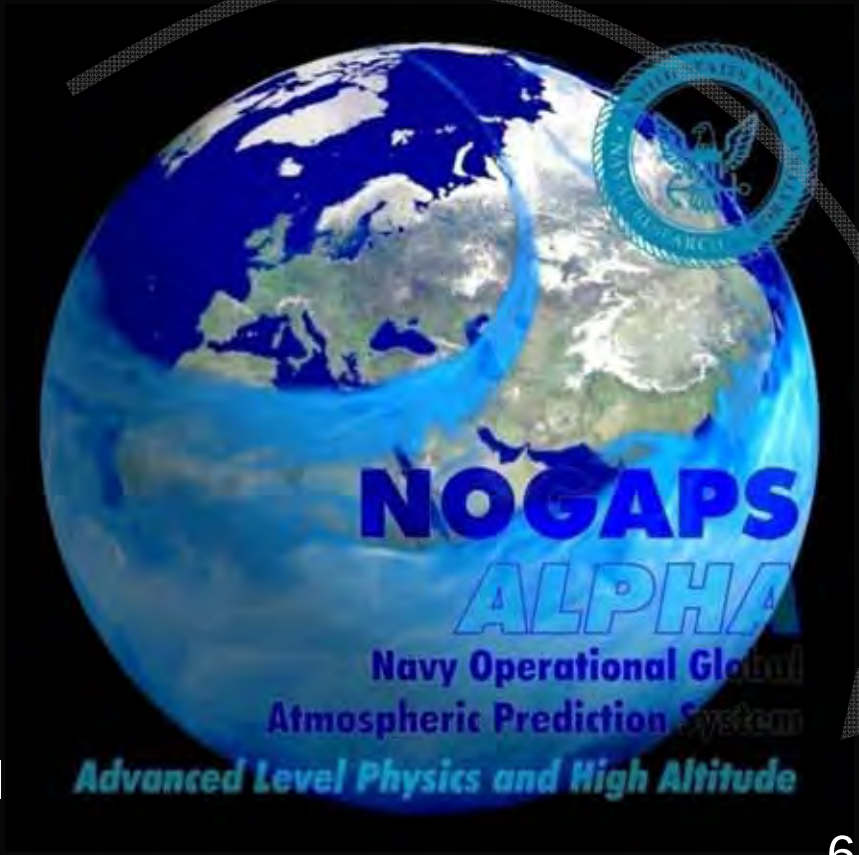
Zonal Winds (m s^{-1})

Temperatures (K)

2. Hybrid Vertical Coordinate

3. Nonorographic Gravity Wave Drag

1. Motivation & R&D History



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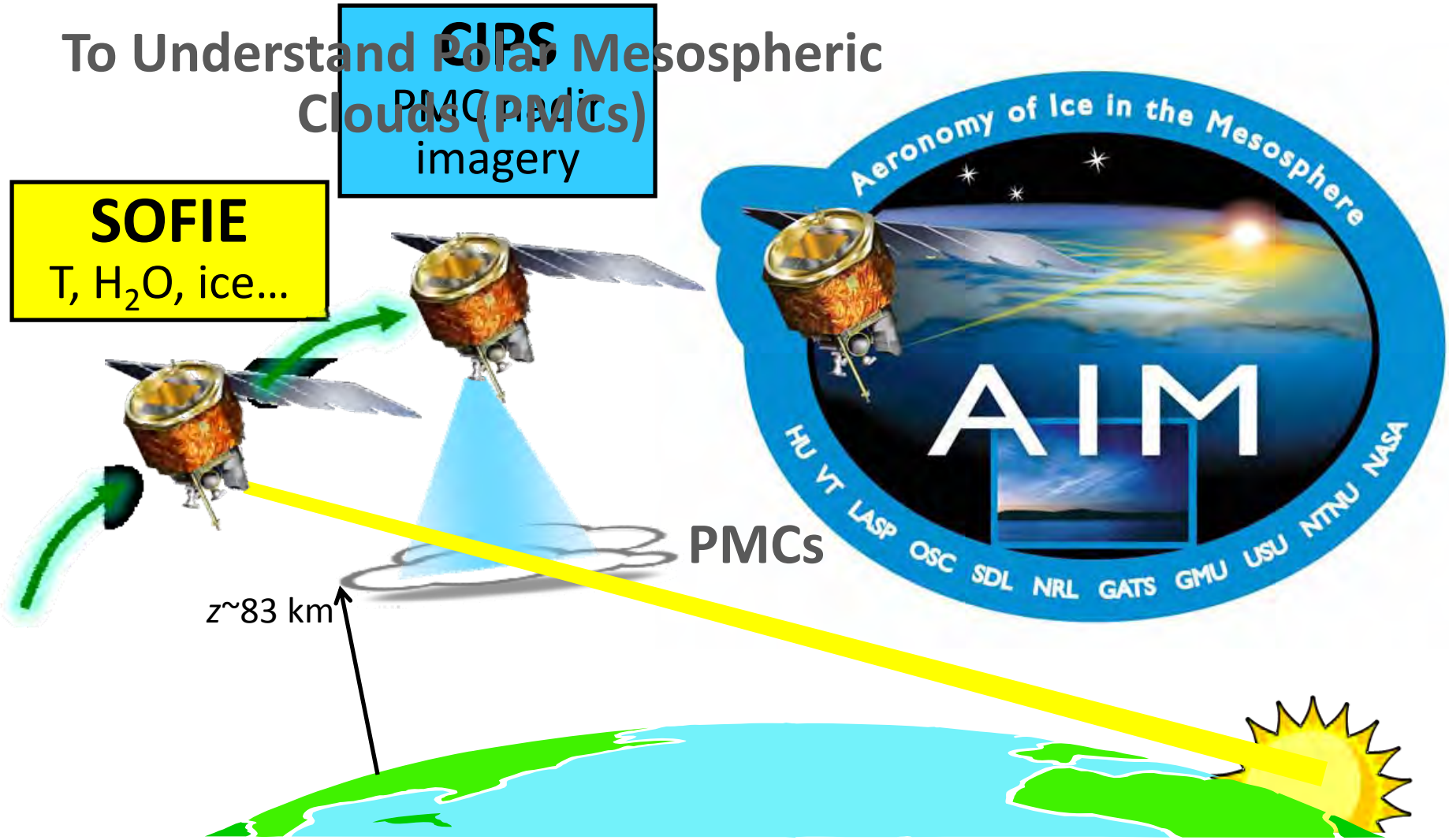
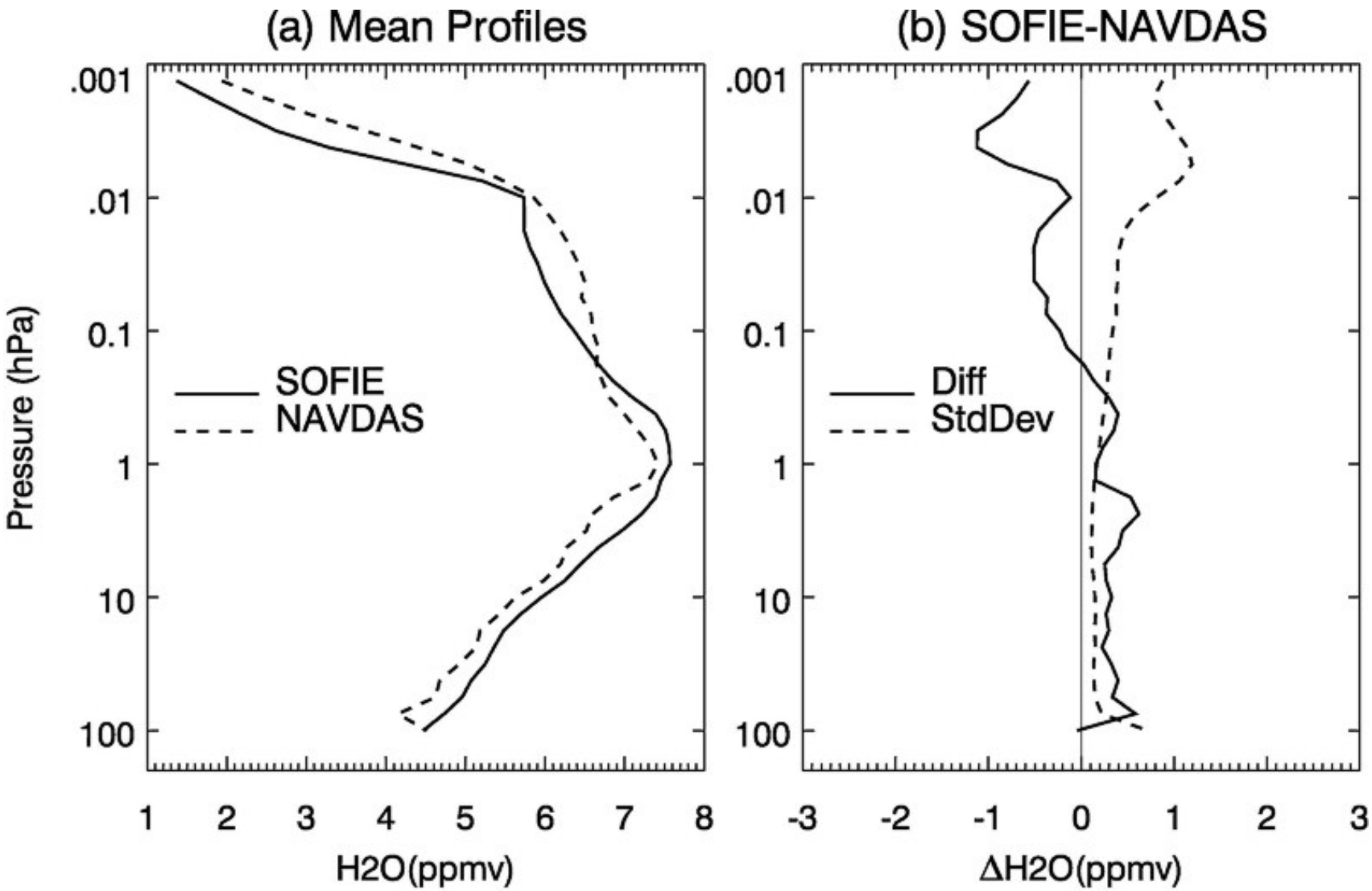
AIM: Aeronomy of Ice in the Mesosphere

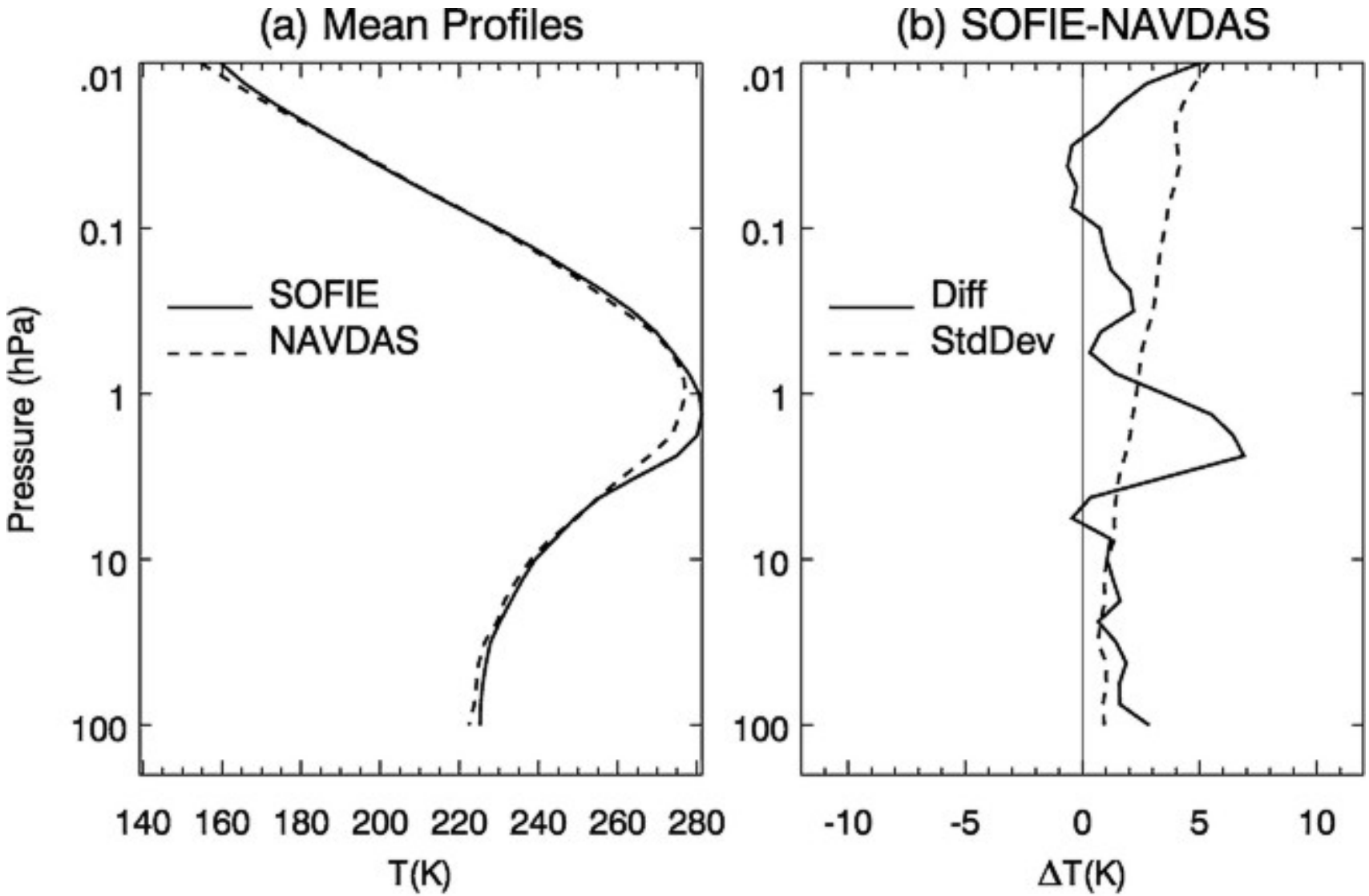
To Understand Polar Mesospheric Clouds (PMCs)



Humidity Validation Against SOFIE (NASA AIM Satellite): 25 May – 23 June 2007

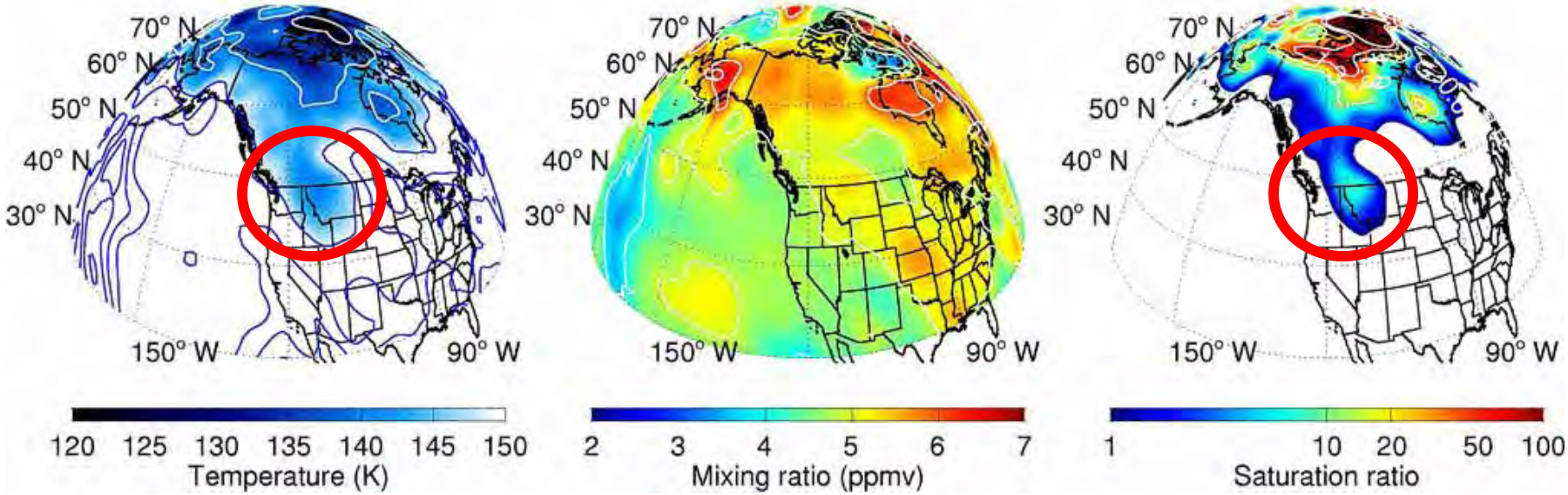


Temperature Validation Against SOFIE (NASA AIM Satellite): 25 May – 23 June 2007



NOGAPS-ALPHA Assimilated Fields
20 June 2007 0600 UTC
0.006 hPa (~83 km)

Temperature T | Water Vapor χ_{H2O} | Saturation Ratio S



$$S = p_{H2O}/p_{ice} \qquad p_{H2O} = p\,\chi_{H2O}$$

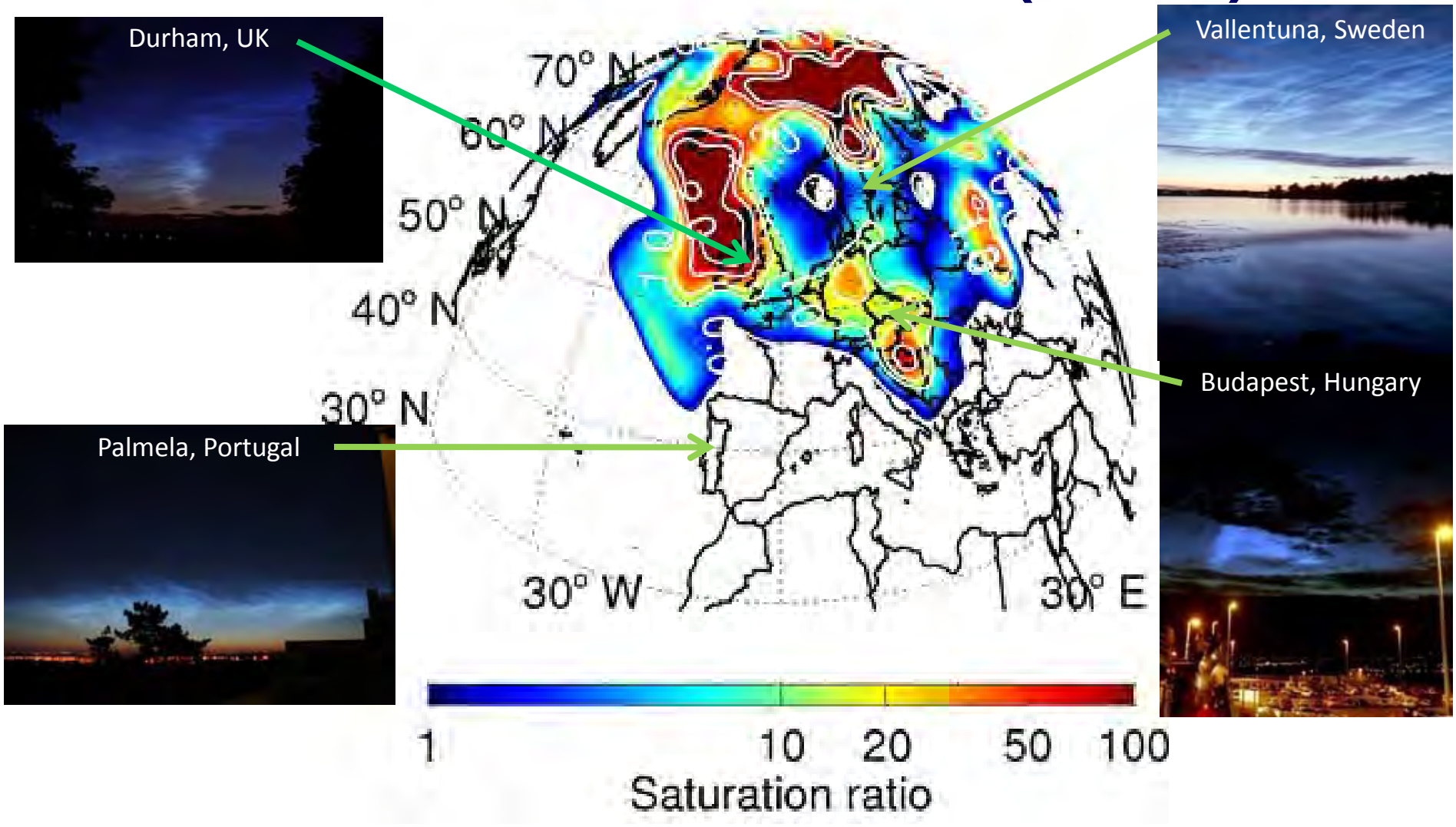
$$\log p_{ice} = 9.550426 - 5723.265/T + 3.53068 \log T - 0.00728332\,T$$

[*Murphy and Koop*, 2005]

Eckermann, S. D., K. W. Hoppel, L. Coy, J. P. McCormack, D. E. Siskind, K. Nielsen, A. Kochenash, M. H. Stevens, C. R. Englert, and M. Hervig, High-altitude data assimilation system experiments for the northern summer mesosphere season of 2007, *J. Atmos. Sol.-Terr. Phys., 71,* 531-551, 2009

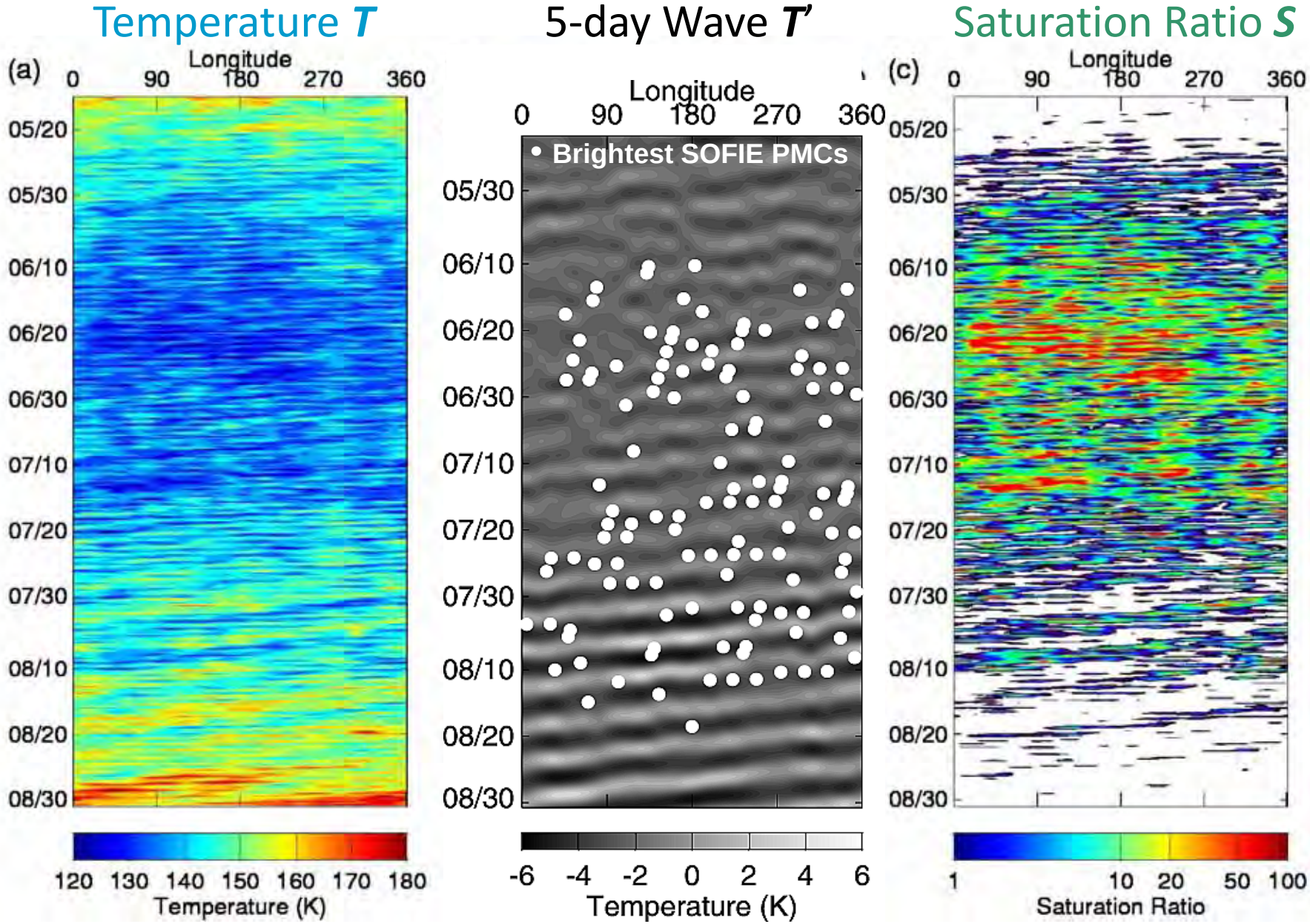
NLC Outbreak over northwestern USA
19 June 2007

NOGAPS-ALPHA Assimilated Fields
30 June 2007 0000 UTC
Saturation Ratio at 0.006 hPa (~83 km)

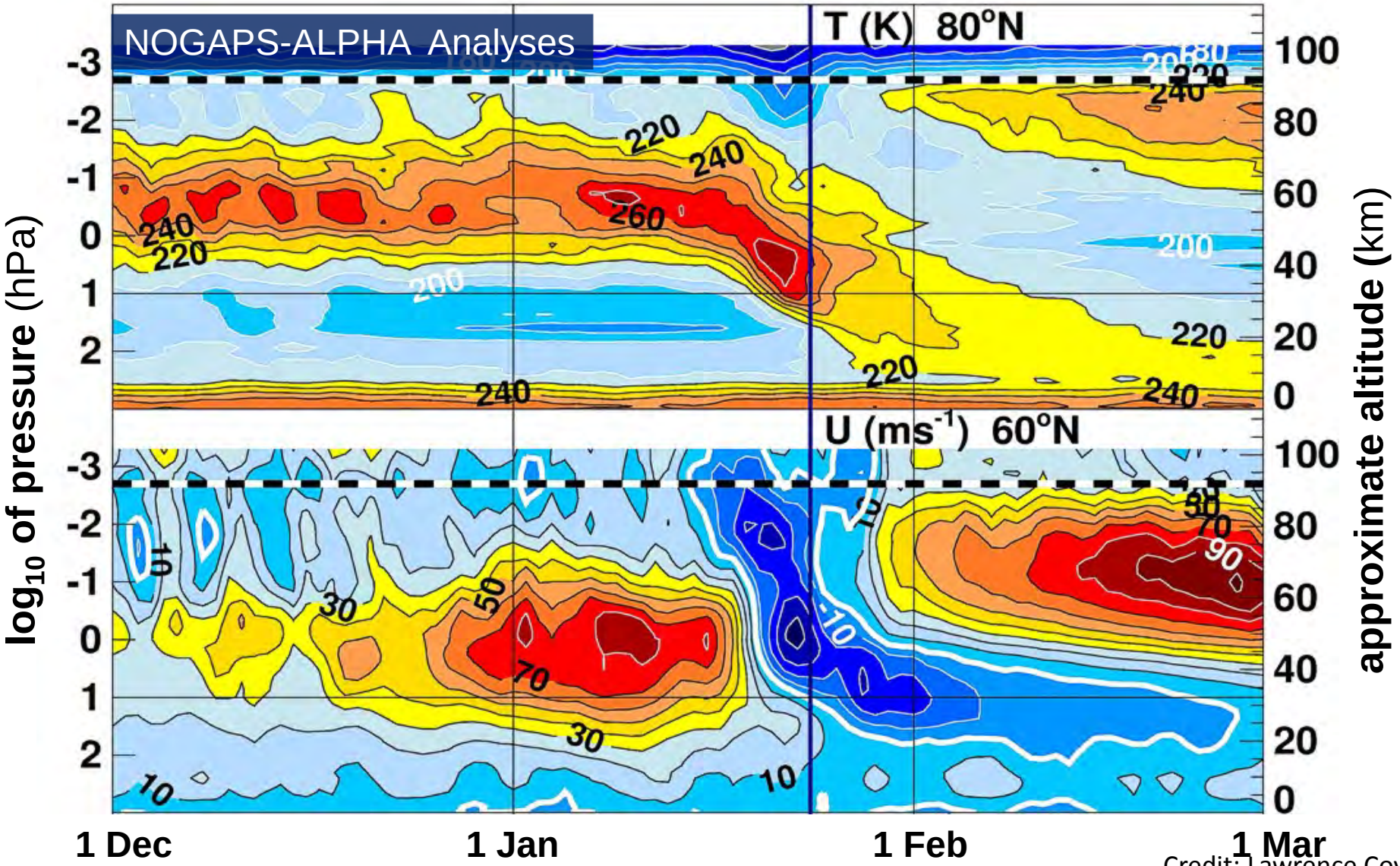


Large-Amplitude 5-day Wave Extends PMC Season into August

Nielsen, K., D. E. Siskind, S. D. Eckermann, K. W. Hoppel, L. Coy, J. P. McCormack, S. Benze, C. E. Randall, and M. E. Hervig (2010), Seasonal variation of quasi 5 day planetary wave: Causes and consequences for polar mesospheric cloud variability in 2007, J. Geophys. Res.,115, D18111.



The Record-Breaking Wave-2 Stratospheric Warming of January 2009 (Changes in AO)



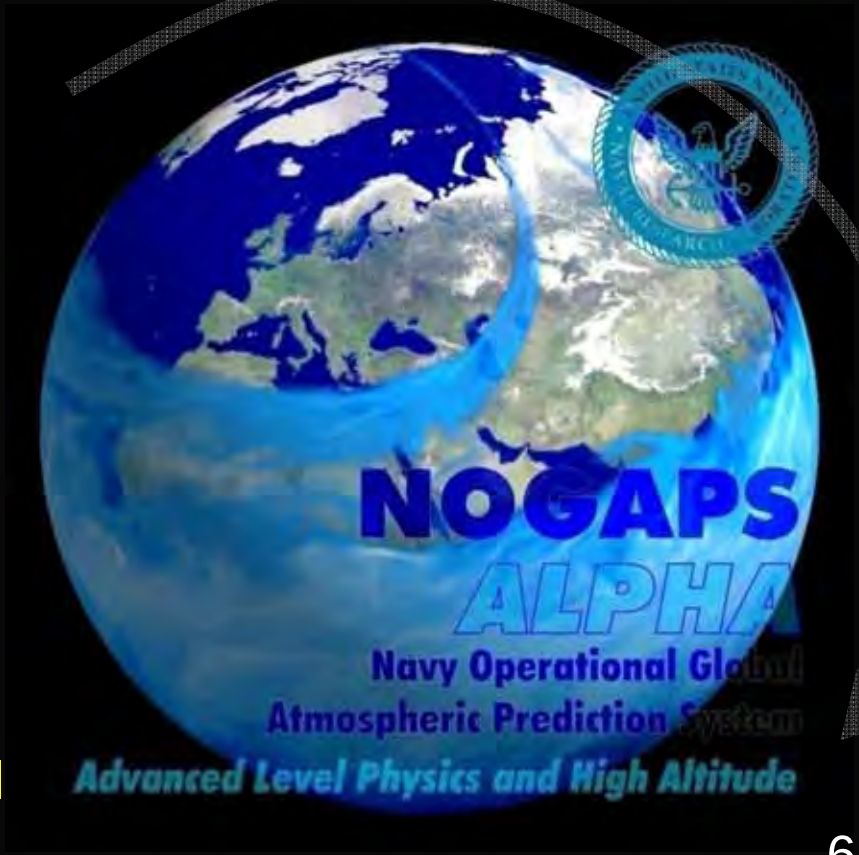
Top Data Insertion Altitude

Credit: Lawrence Coy
lawrence.coy@nrl.navy.mil

2. Hybrid Vertical Coordinate

3. Nonorographic Gravity Wave Drag

1. Motivation & R&D History



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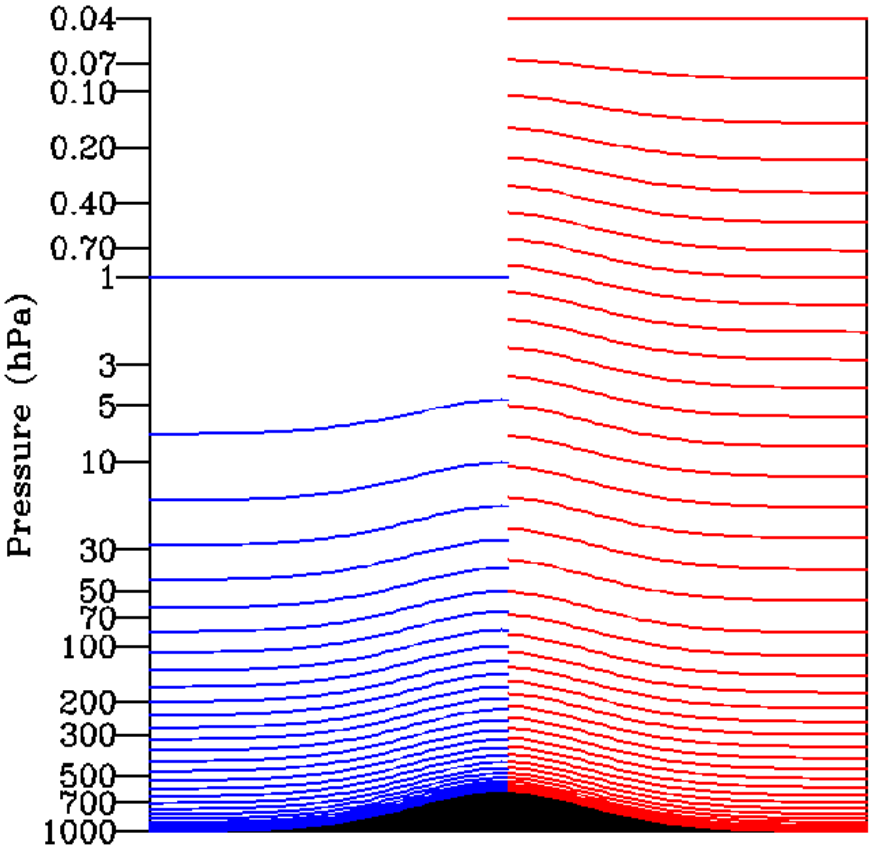
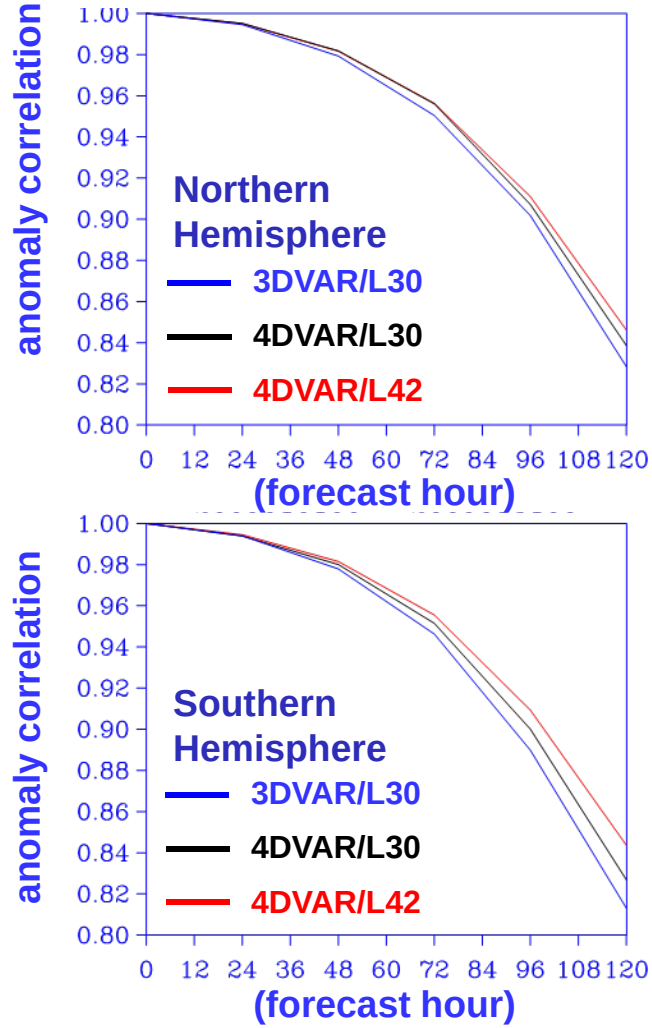
Operational NOGAPS Changes

From 3DVAR/T239L30 sigma
to 4DVAR/T239L42 sigma
Operational on 23 September 2009



3DVAR → 4DVAR
L30 z_{top}=45 km → L42 z_{top}=70 km

500 hPa Geopotential-Height
Anomaly Correlations
1-31 January 2009

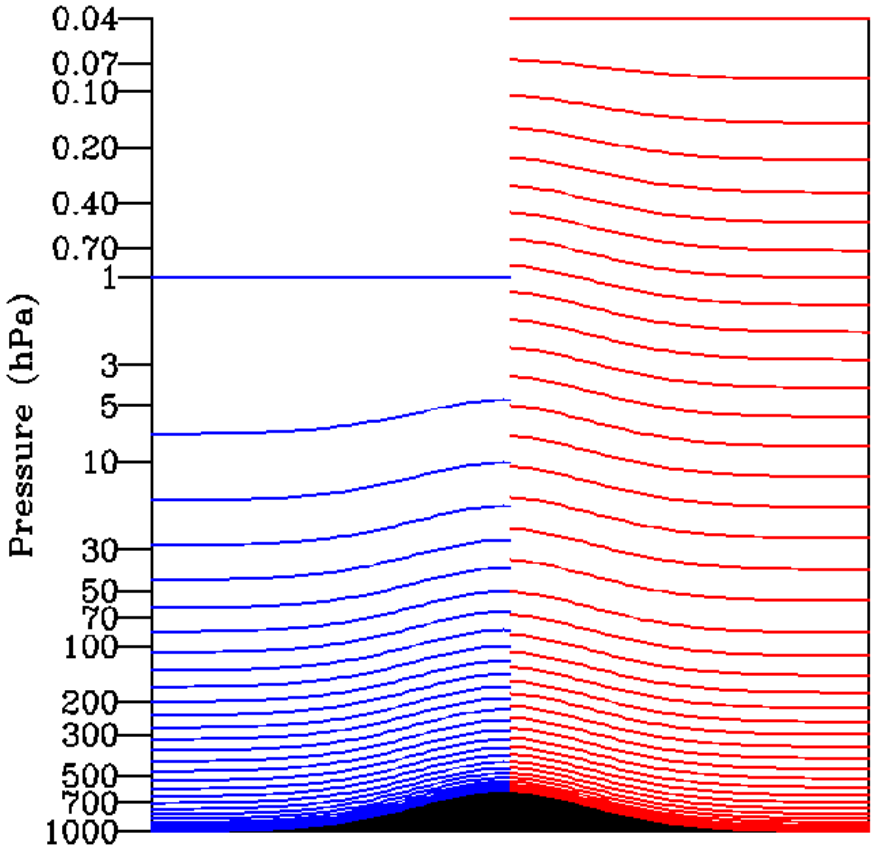


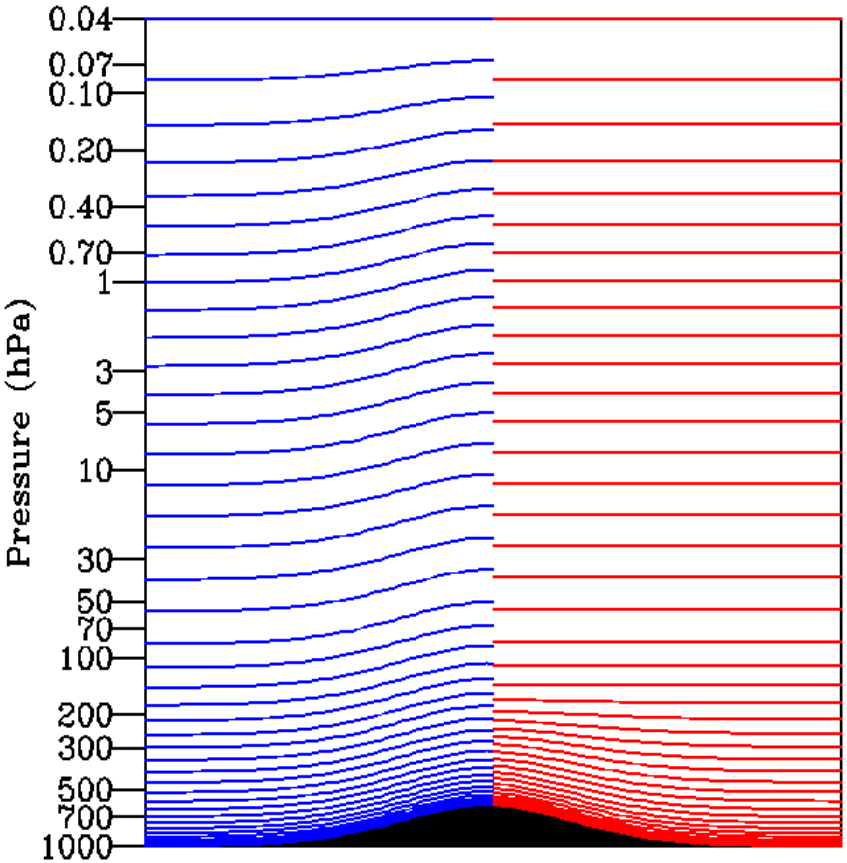
Credit: Tim Hogan & Nancy Baker
timothy.hogan@nrlmry.navy.mil

Operational NOGAPS Changes

From 3DVAR/T239L30 sigma
to 4DVAR/T239L42 sigma
Operational on 23 September 2009

From 4DVAR/T239L42 sigma
to 4DVAR/T319L42 hybrid
Operational on 18 May 2010



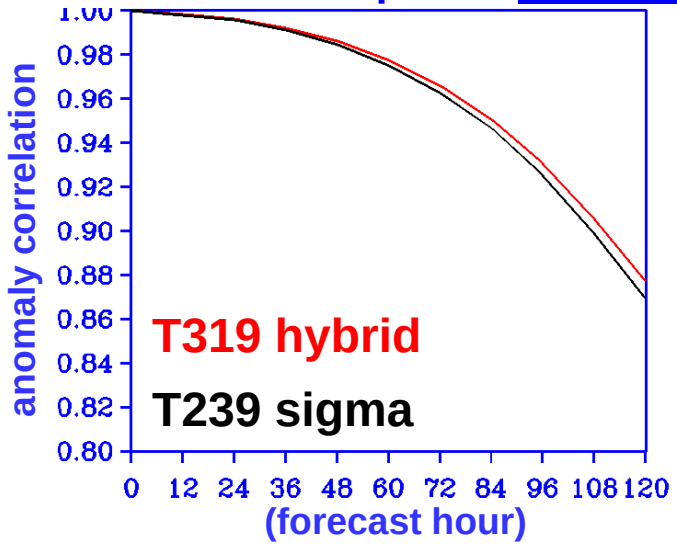


3DVAR → 4DVAR
L30 z_{top}=45 km → L42 z_{top}=70 km

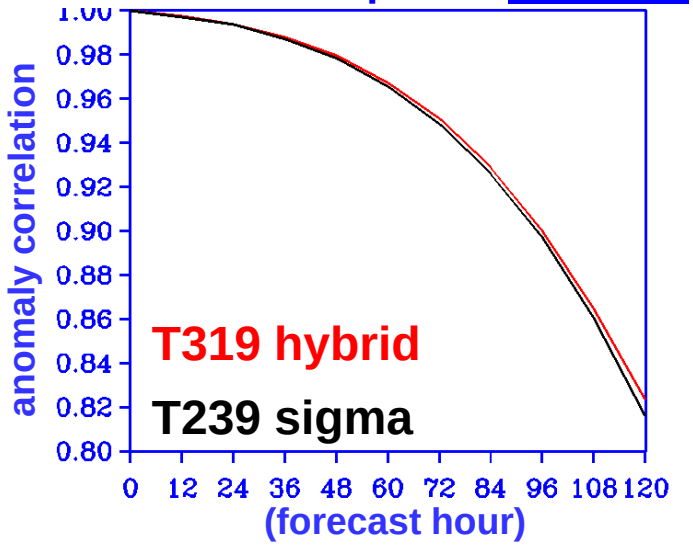
sigma coordinate → hybrid sigma-p
T239 → T319

T239 σ-coordinate → T319 hybrid σ-*p* coordinate

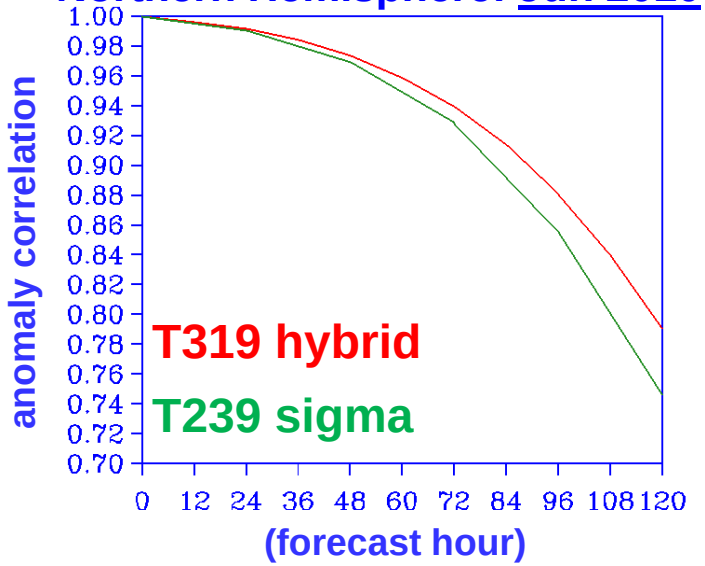
Northern Hemisphere: Jan 2010



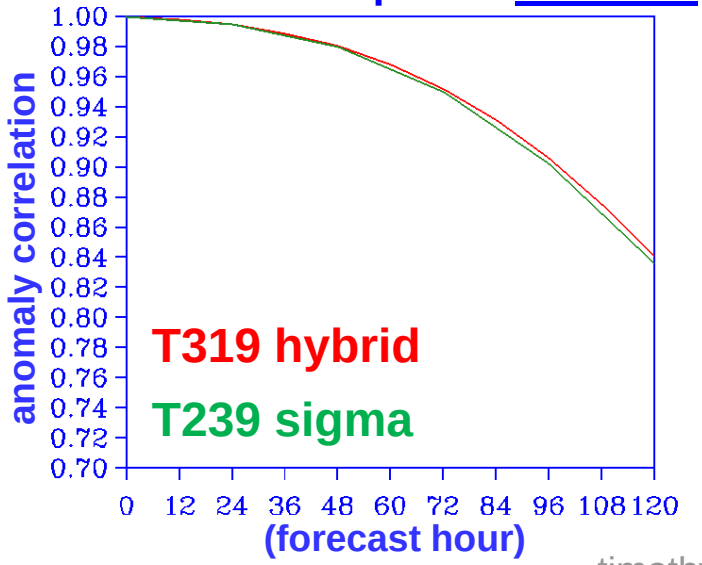
Southern Hemisphere: Jan 2010



Northern Hemisphere: Jun 2010



Southern Hemisphere: Jun 2010

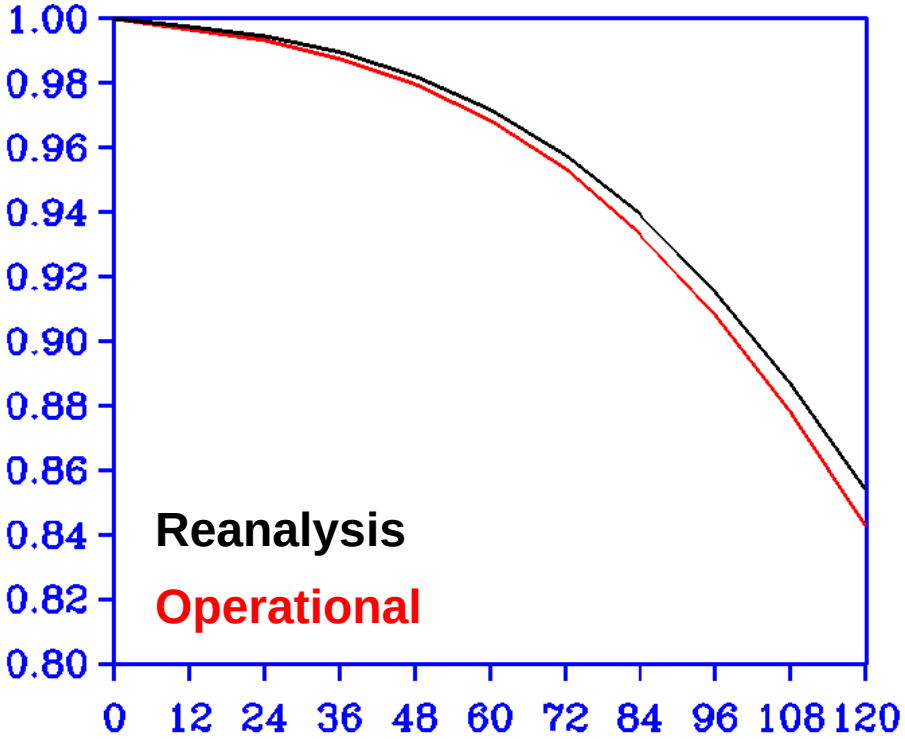


500 hPa Geopotential Height Anomaly Correlations

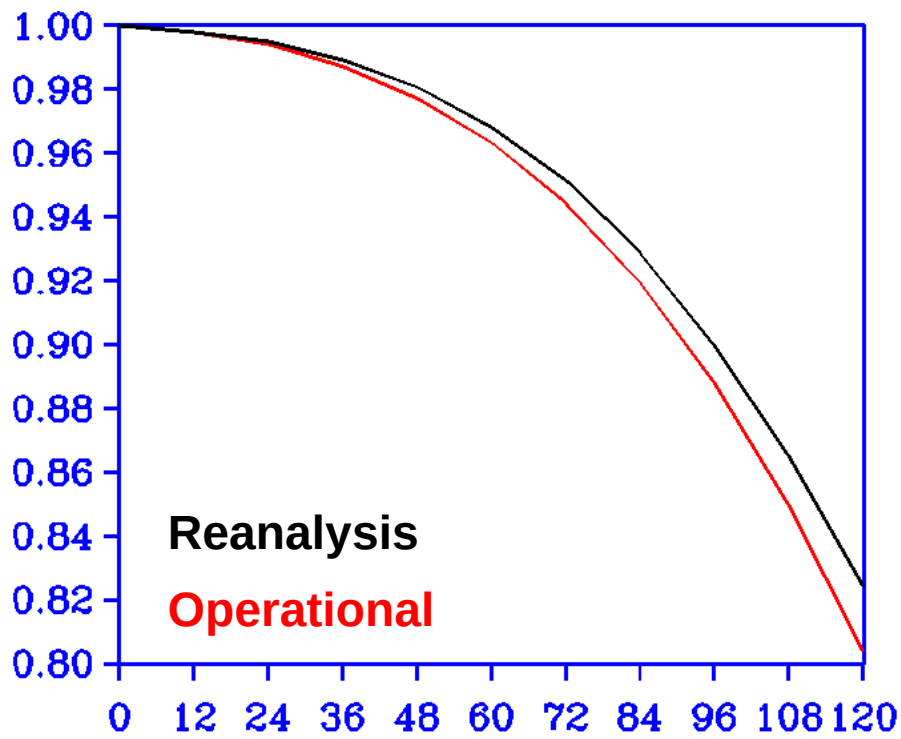
Credit: Tim Hogan
timothy.hogan@nrlmry.navy.mil

Impact of September 2010 Update
500 hPa Height Anomaly Correlation

Assimilation of GPS BA, additional IR/MW stratospheric channels, IASI channels over land/sea-ice



Northern Hemisphere



Southern Hemisphere

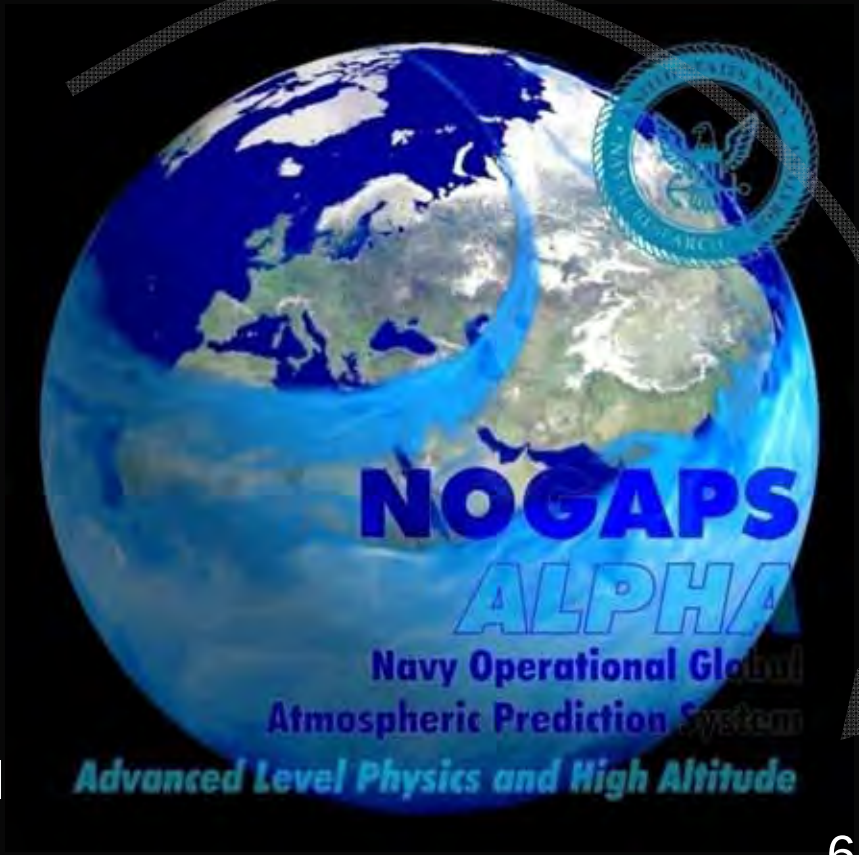
July 1-September 6 2010

Credit: Tim Hogan, Ben Ruston
timothy.hogan@nrlmry.navy.mil

2. Hybrid Vertical Coordinate

3. Nonorographic Gravity Wave Drag

1. Motivation & R&D History



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Summary

- The NOGAPS-ALPHA prototype has successfully demonstrated the feasibility of operational NWP from ground to edge of space (0-100 km)
- NOGAPS-ALPHA technology is progressively transitioning to NOGAPS where it has led to positive NWP impacts at all altitudes
- The first ground-to-100 km DAS products from NOGAPS-ALPHA have found many scientific research applications (e.g., AIM PMC science)

Outlook/Plans

- Extending NOGAPS/AR to ~100 km as new “ALPHA” prototype of 4DVAR/SLFM
- New fast operational HA physics (gravity-wave drag, non-LTE radiation)
- Assimilation of mesospheric thermal radiances (e.g., SSMIS, Zeeman, CRTM…)
- Operational assimilation of stratospheric humidity with photochemistry (AMSU-B)
- Mesospheric ozone assimilation (diurnal ozone photochemistry, interactive SW)
- Multivariate assimilation of ozone and water vapor (e.g., O_3 ←→ winds)
- Lower thermospheric physics & data assimilation (>100 km)