
Performance of the ECMWF Model in Polar Regions

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ECMWF

(ECMWF Annual Seminar on Polar Meteorology)

Thanks to: Martin Leutbecher + colleagues from RD

Outline

- **Analysis**
- **Predictability issues**
- **Specific Phenomena**
- **Systematic Error**

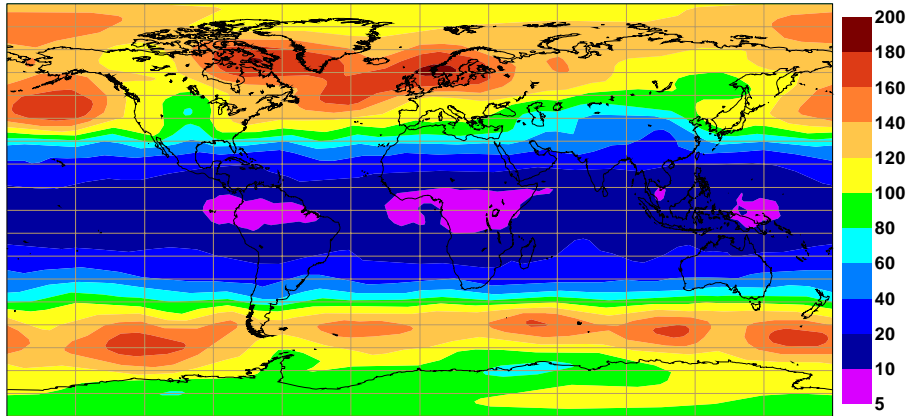
Focus

- **Region**
 - Primarily Northern Hemisphere
- **Season**
 - Boreal winter (DJF and DJFM)
- **Atmospheric circulation**

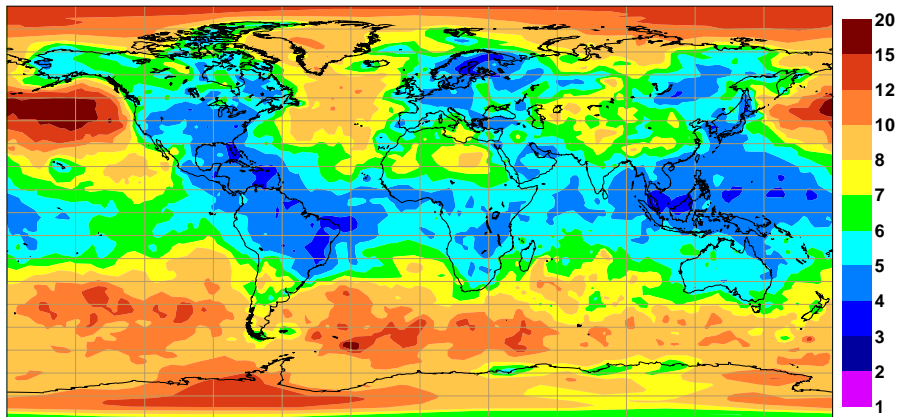
ERA-40 vs Operational Analysis

Total Z500 Variability

(a) Standard Deviation: Total Z500 Variability (ERA40, 2000-01)

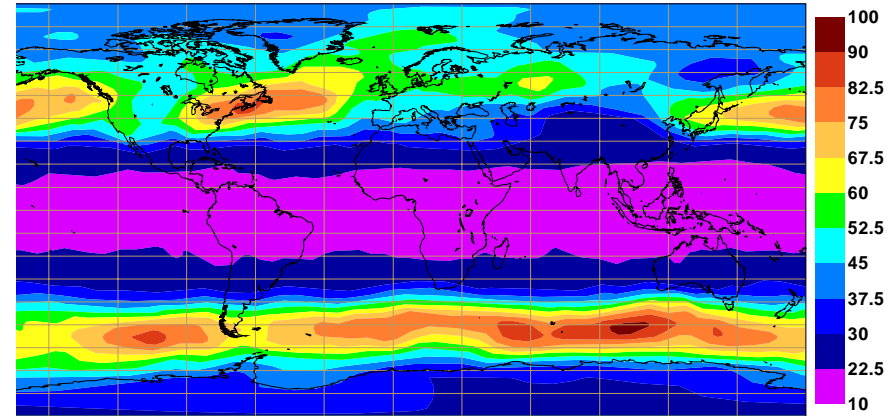


(b) Standard Deviation: Difference OD-ERA40 (2000-01)

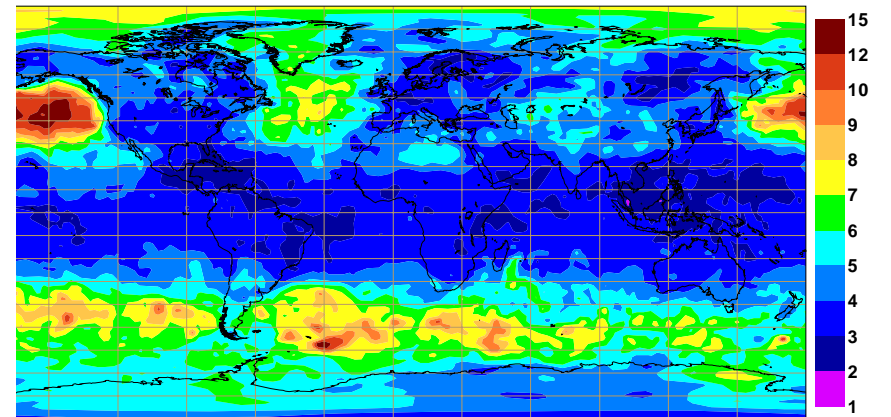


Synoptic Z500 Variability

(a) Standard Deviation: Synoptic Z500 Variability (OD DJF 2000-01)

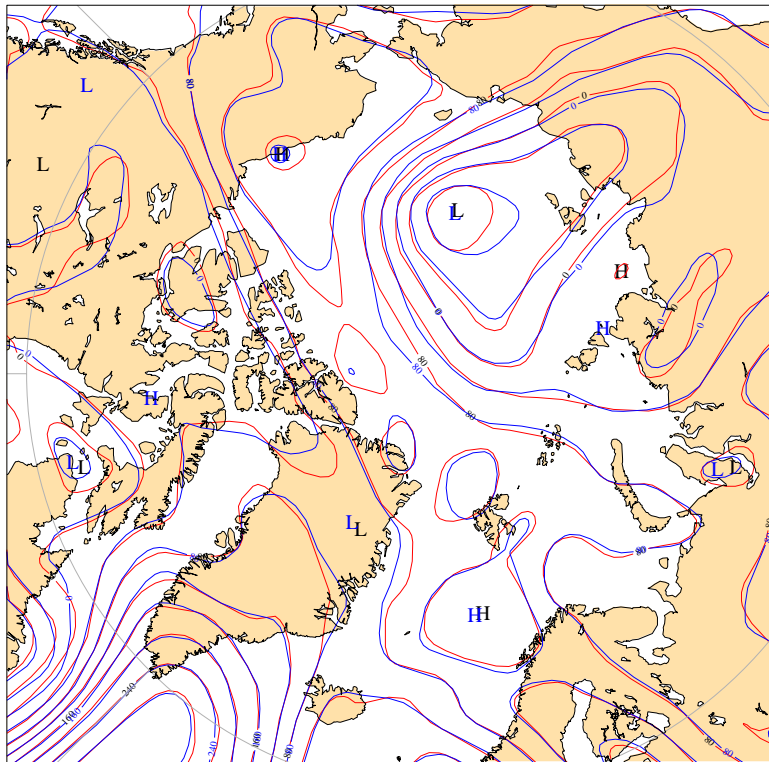


(b) Standard Deviation: Difference OD-E4 (Synoptic, DJF 2000-01)

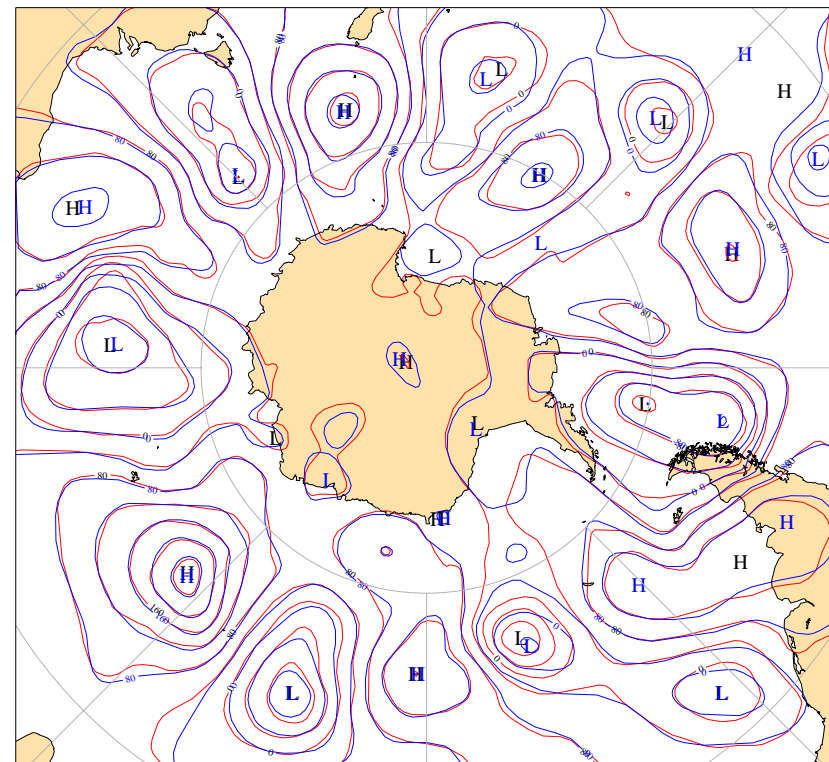


Synoptic-Scale Z500 Snapshots

3 December 2000 12UTC



7 December 2000 12UTC

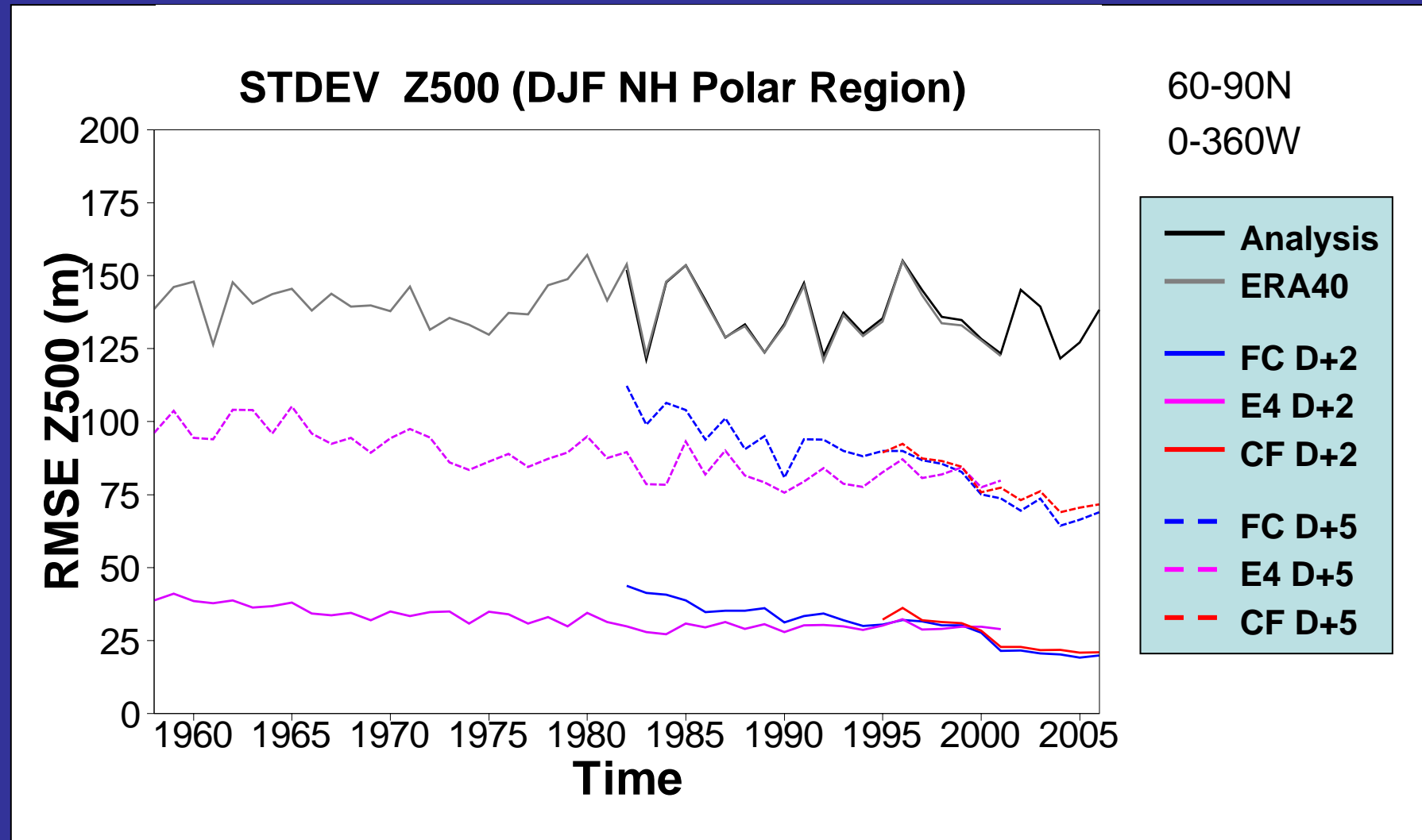


2-8 day bandpass-filtered data

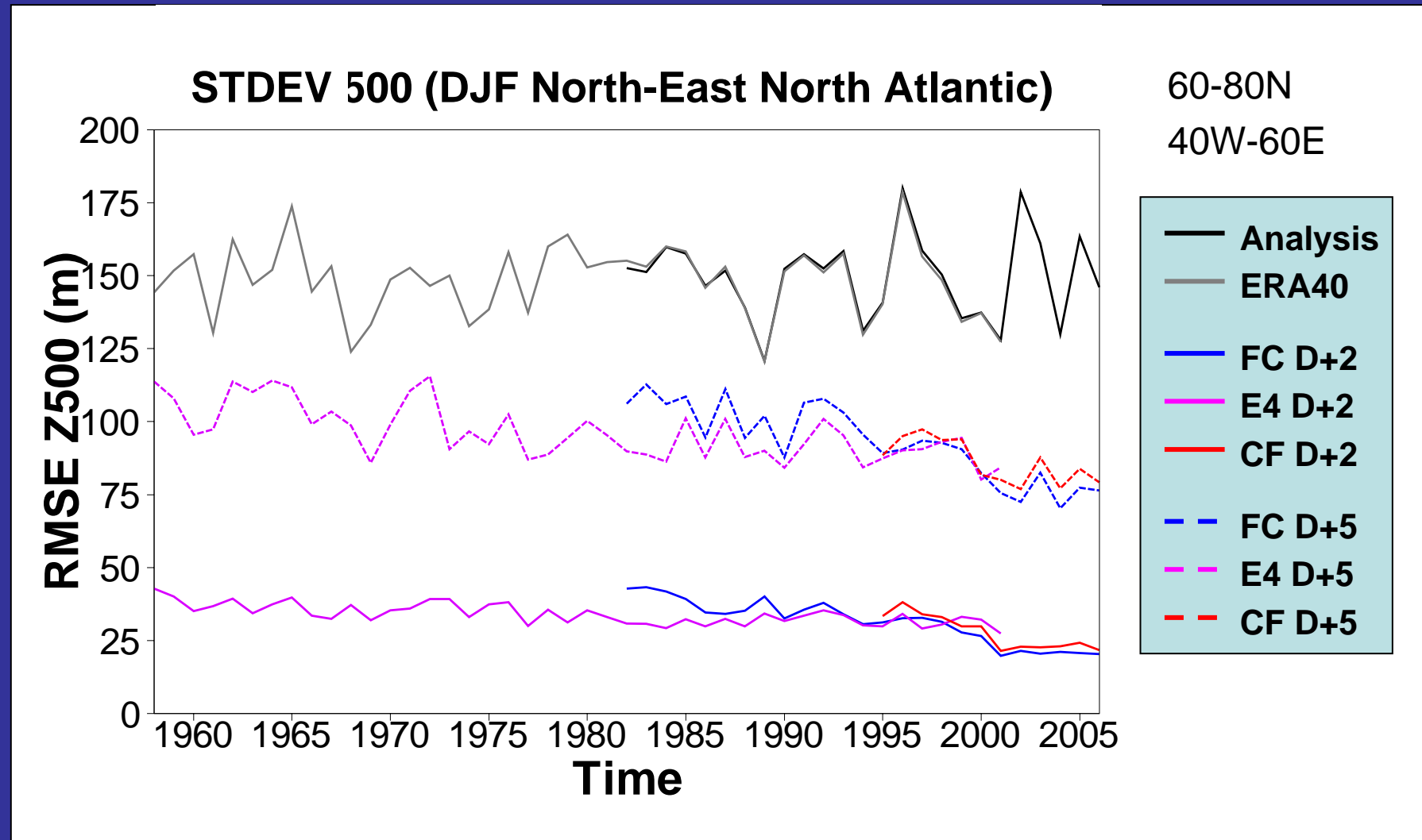
Conclusions

- **Analyzed circulation seems good enough for the purposes of this study**
- **This is true for synoptic and planetary scales**
- **Clearly improvement in recent years**

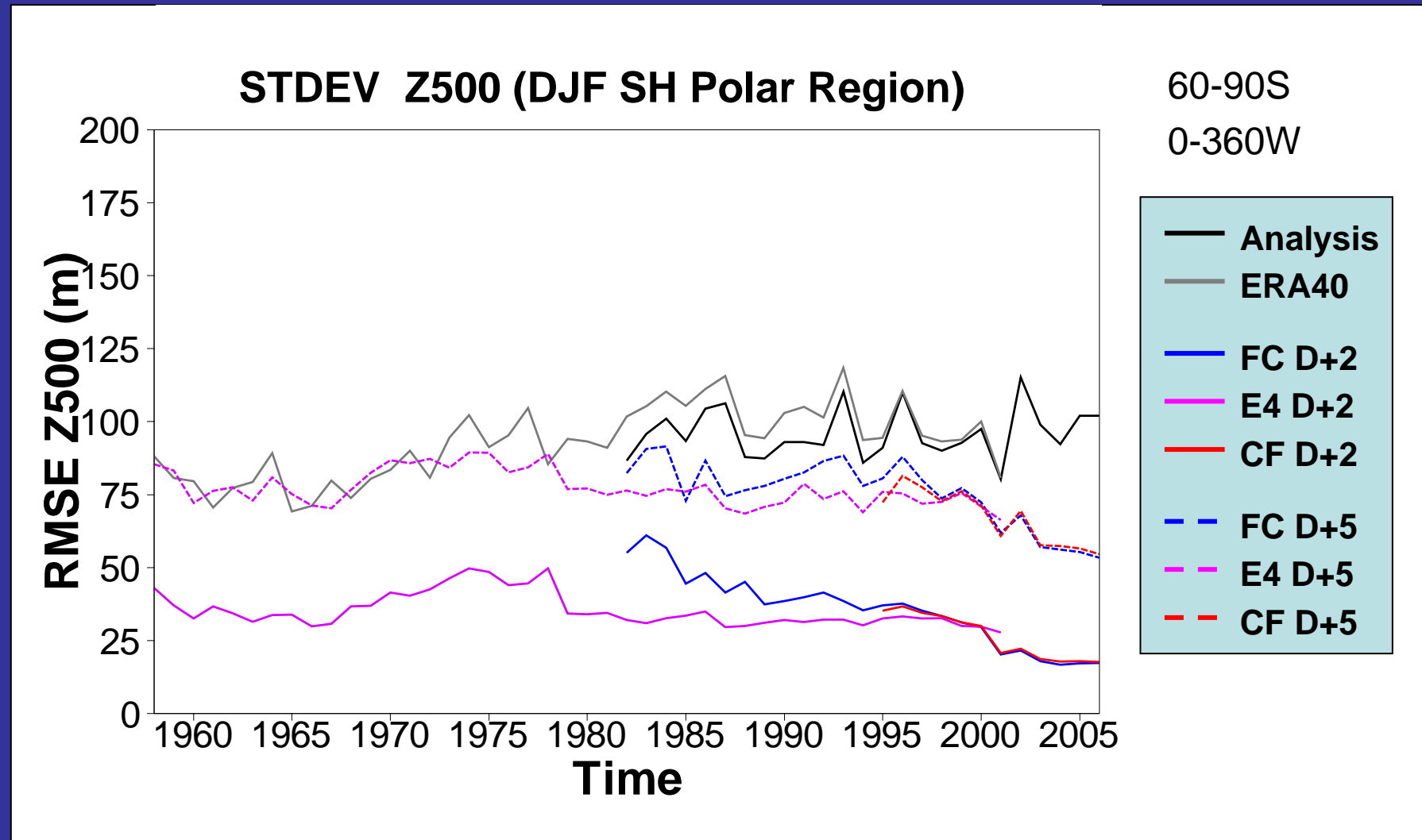
Temporal Evolution of Deterministic Forecast Error



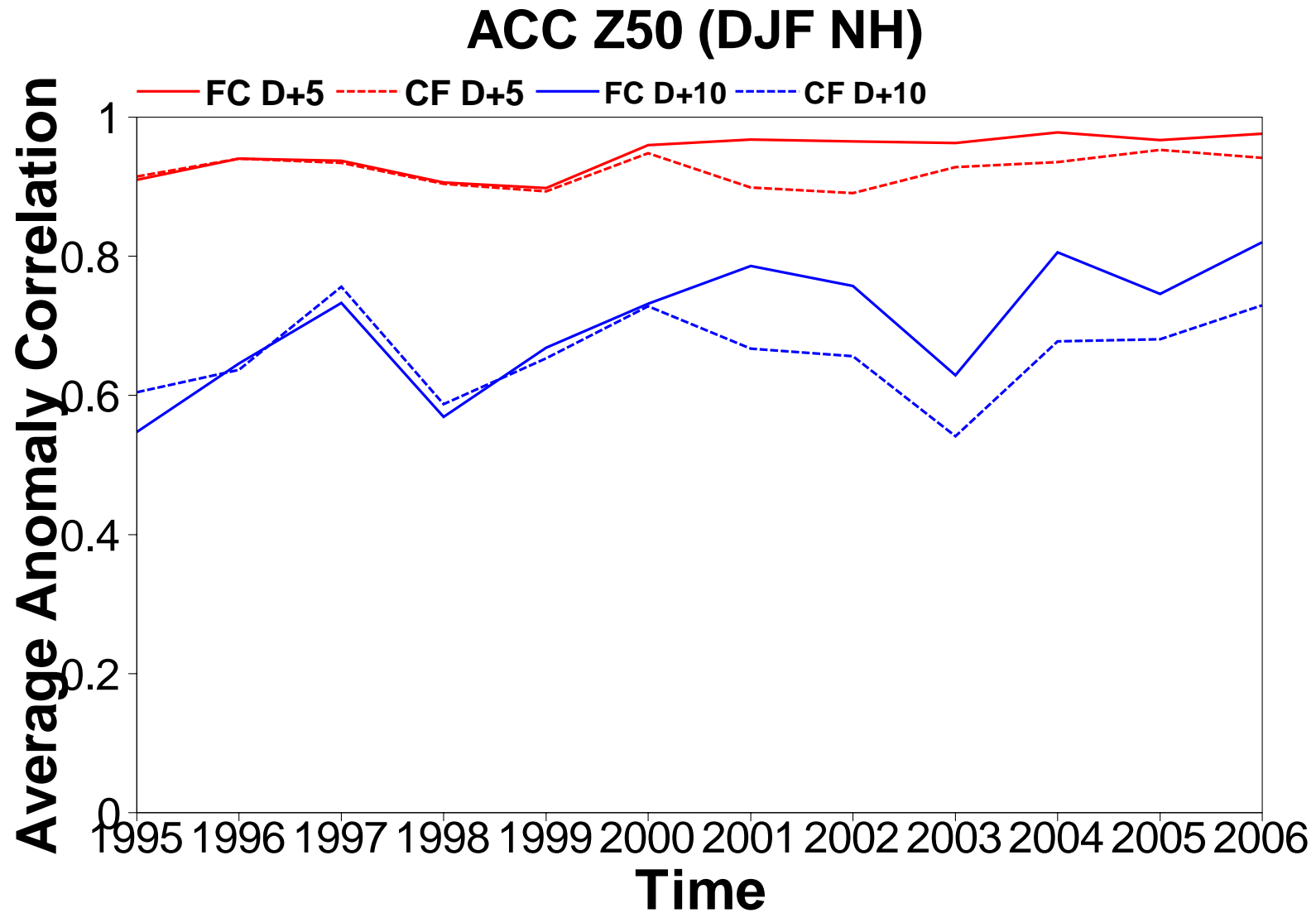
Temporal Evolution of Deterministic Forecast Error



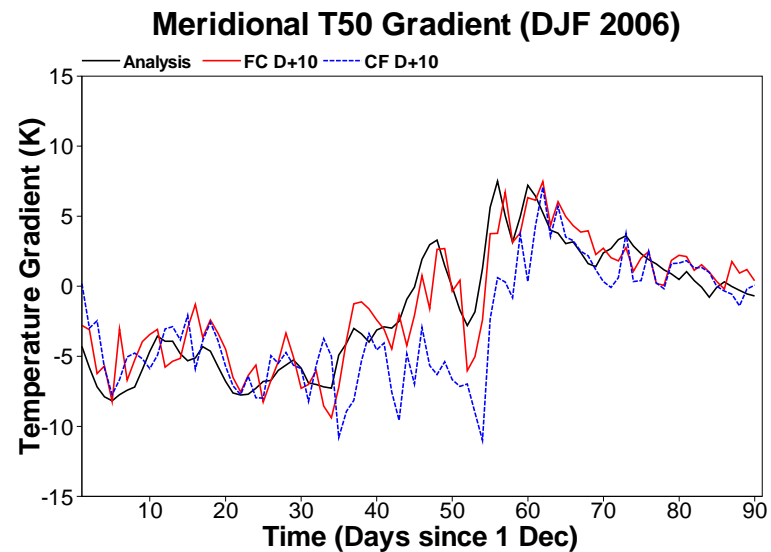
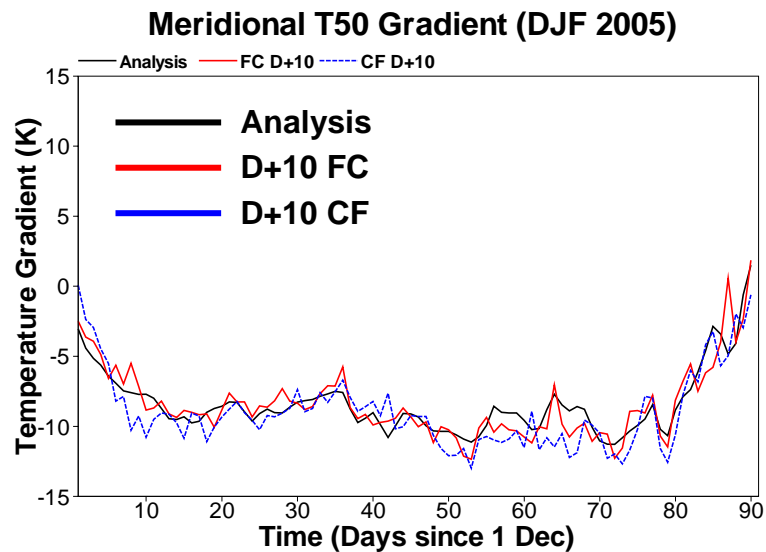
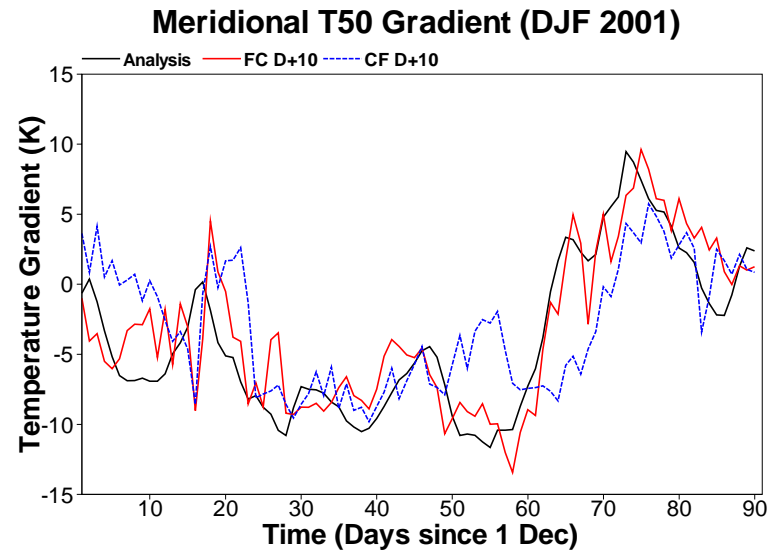
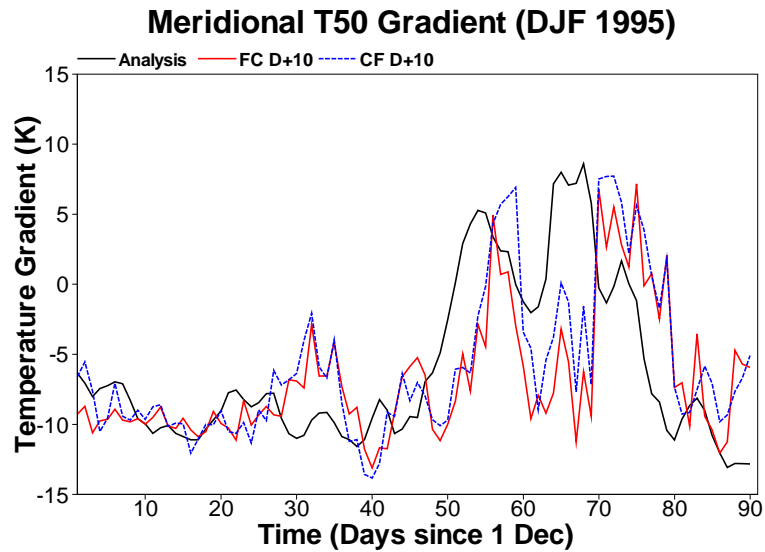
Temporal Evolution of Deterministic Forecast Error



ACC Z50 DJF NH: 1995-2006



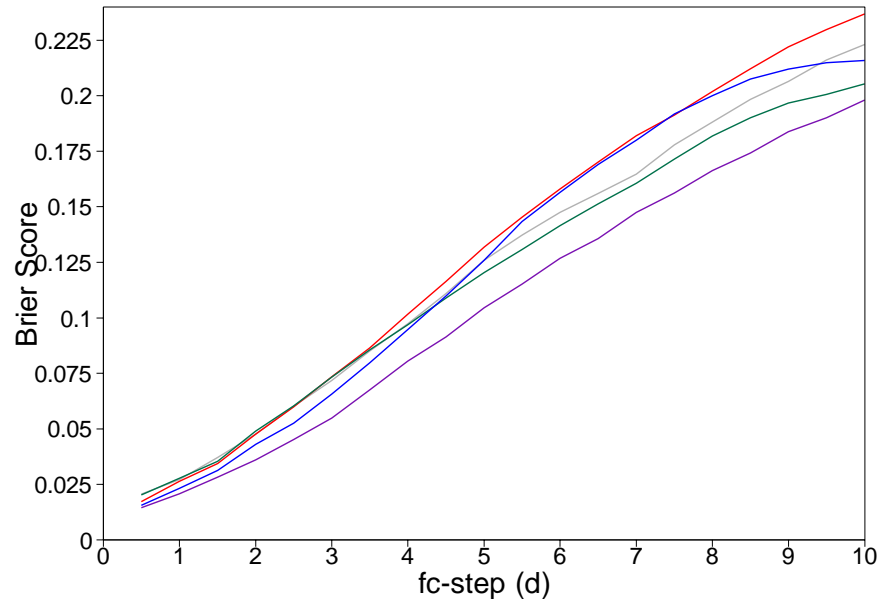
Time Series of the Meridional Temperature Gradient



Probabilistic Skill: NH Polar Cap

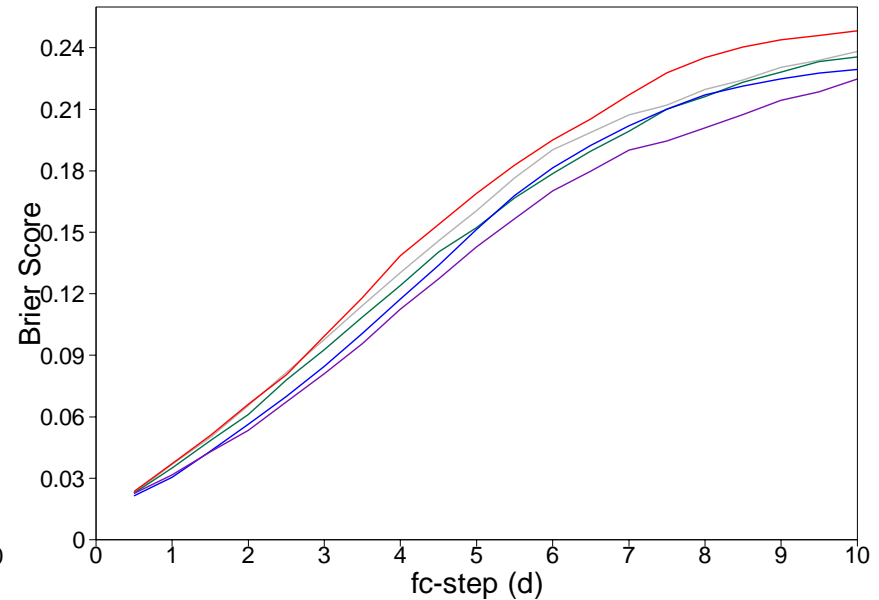
All Scales

z1000hPa at 1000, anomaly>0.0 stdev; area: n.pole, T0-63LL
grey: 2002;red: 2003;evergreen: 2004;blue: 2005;violet: 2006
sample of 90 cases; 2005120112 - 2006022812



Synoptic Scales Only

z1000hPa at 1000, anomaly>0.0 stdev; area: n.pole, T8-63LL
grey: 2002;red: 2003;evergreen: 2004;blue: 2005;violet: 2006
sample of 90 cases; 2005120112 - 2006022812



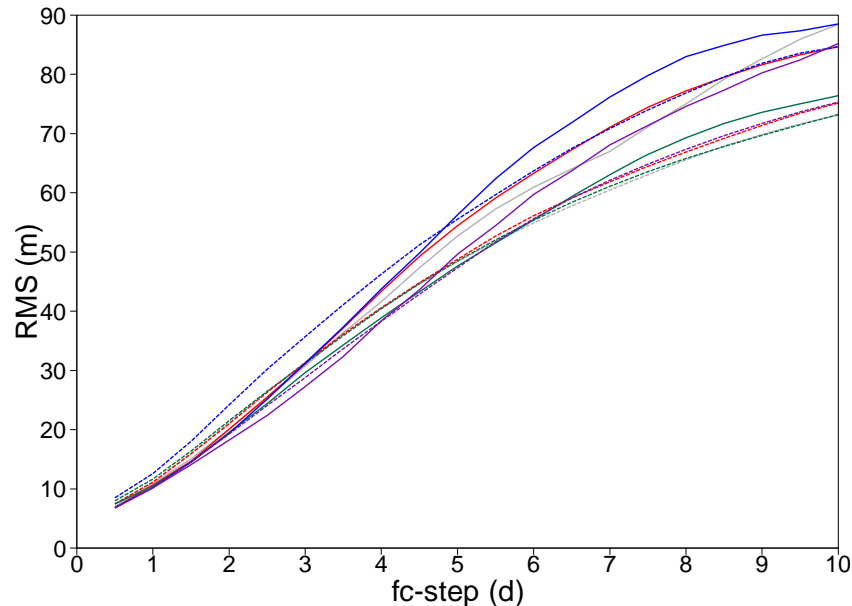
Polar Cap=north of 65N

Courtesy of Martin Leutbecher

EPS Skill vs. Spread: NH Polar Cap

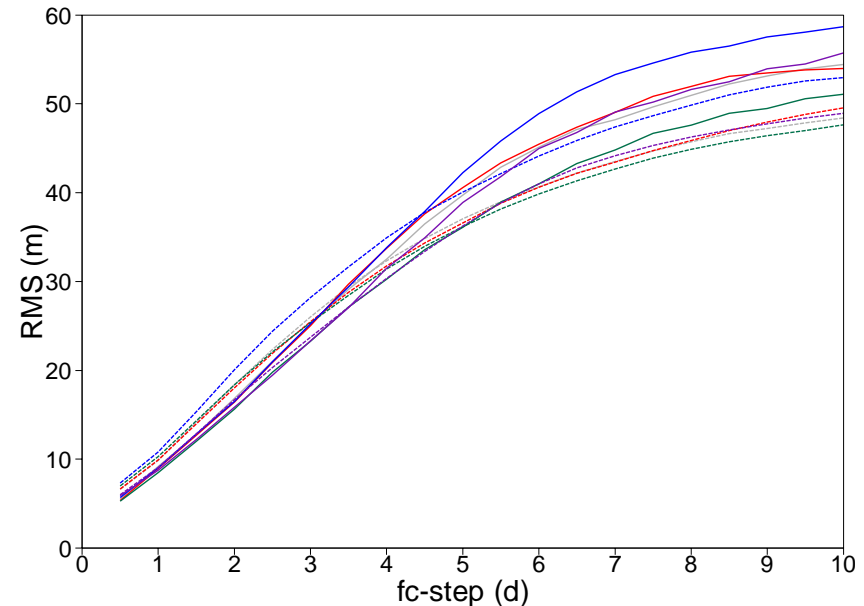
All Scales

z1000hPa; area: n.pole, T0-63LL
grey: 2002; red: 2003; evergreen: 2004; blue: 2005; violet: 2006
solid: RMS error of em, dashed: spread around em
sample of 90 cases; 2005120112 - 2006022812



Synoptic Scales Only

z1000hPa; area: n.pole, T8-63LL
grey: 2002; red: 2003; evergreen: 2004; blue: 2005; violet: 2006
solid: RMS error of em, dashed: spread around em
sample of 90 cases; 2005120112 - 2006022812



Solid lines: RMSE of EM
Dashed lines: Ensemble spread

Courtesy of Martin Leutbecher

Sensitivity of Forecast Error to Initial Conditions

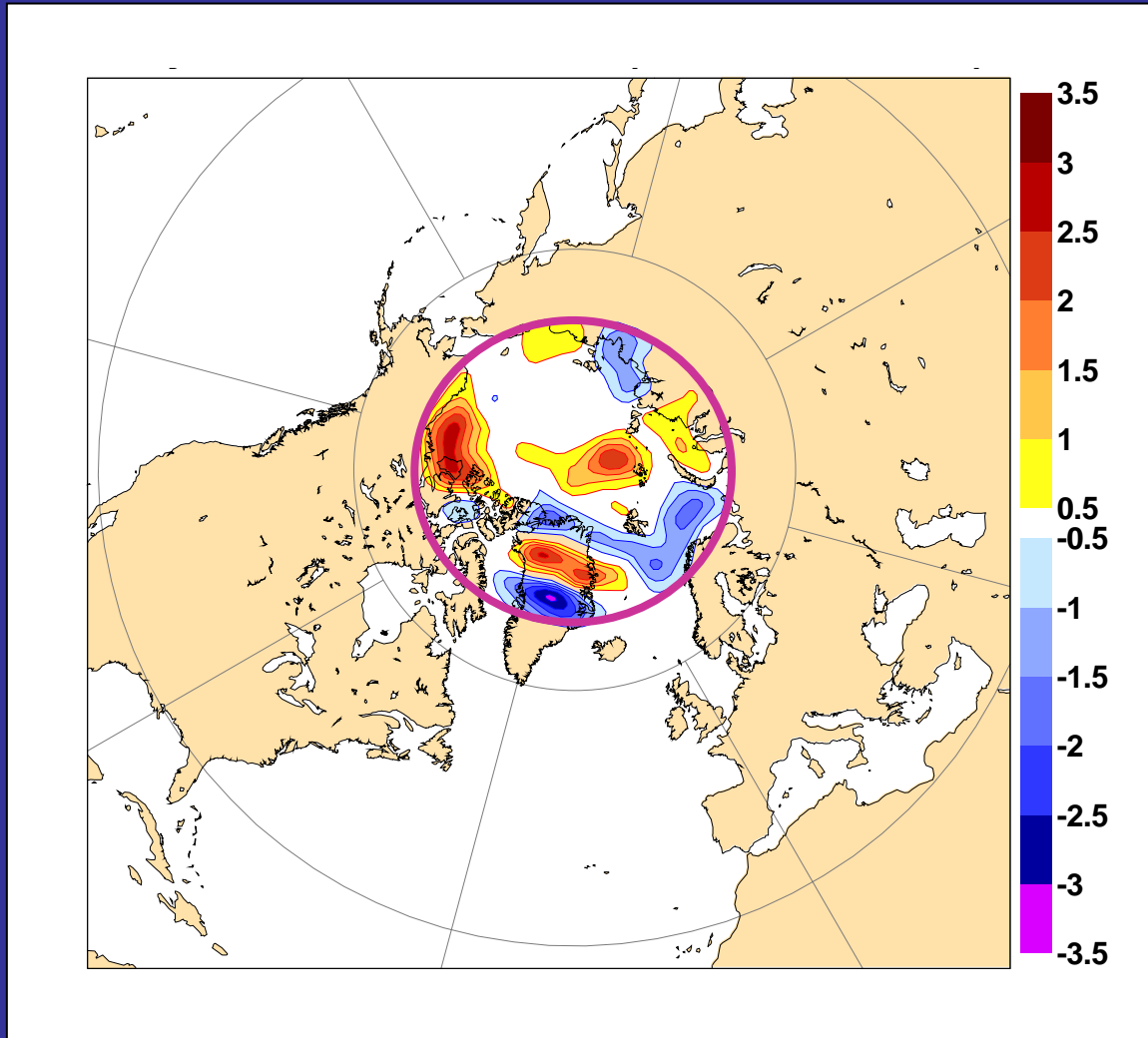
Q: How do perturbations to the initial conditions look like that have a large impact on forecast error north of 70N?

$$\nabla_0 J$$

$$\delta J = \langle \nabla_0 J, \delta \mathbf{x}_0 \rangle$$

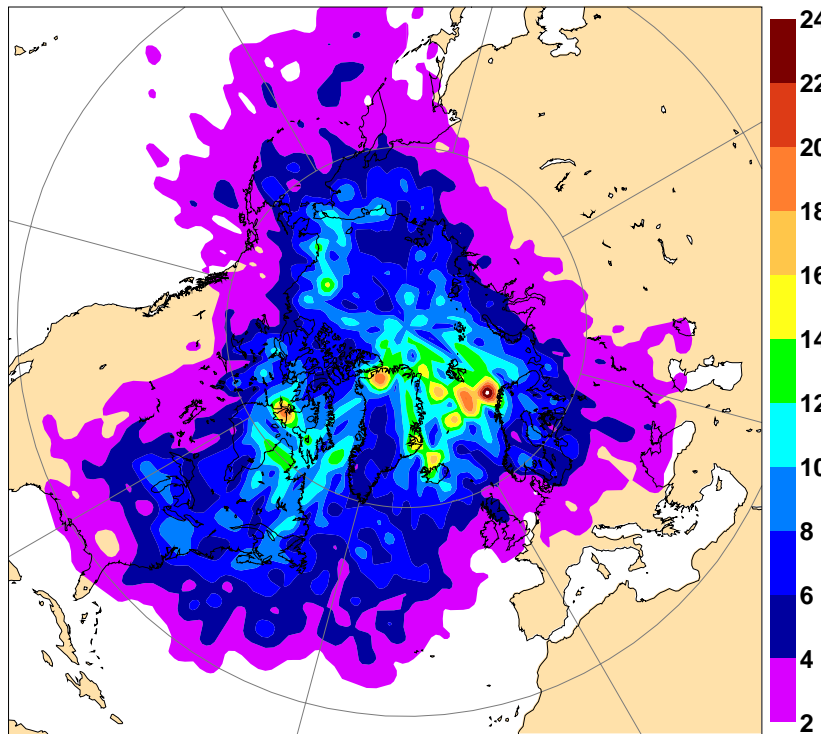
- T159L60 TL/AD
- linearized physical processes
- Target: north of 70N
- 48 hour forecast error

D+2 Forecast Error in Polar Regions: Temperature at about 500 hPa (20041129)

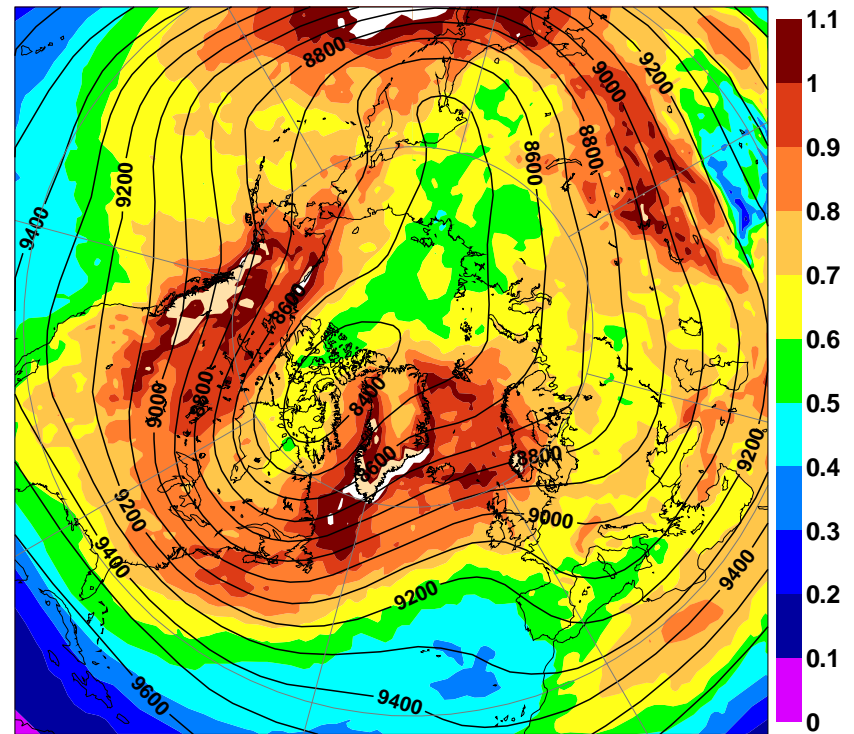


Forecast Sensitivity (DJFM 2004/05) to Initial Perturbations

Mean Absolute Value: T-Sensitivity at about 500hPa

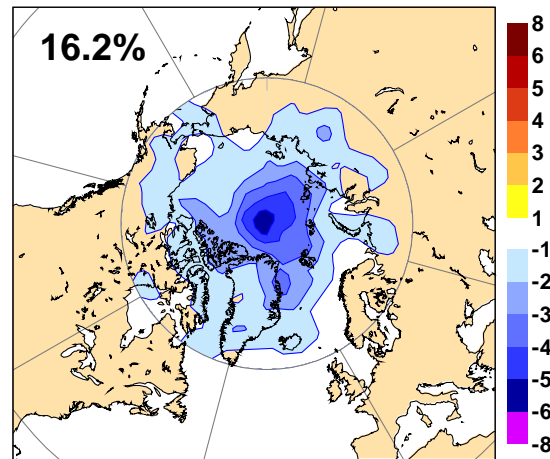


Eady Index, Z500

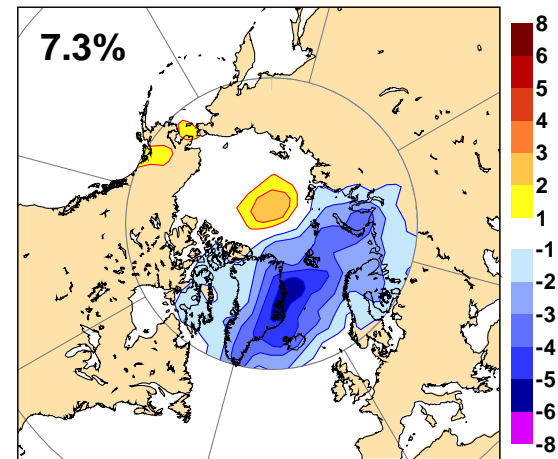


Flow-Dependent Deterministic Forecast Error (D+2, DJF, 1982-2001)

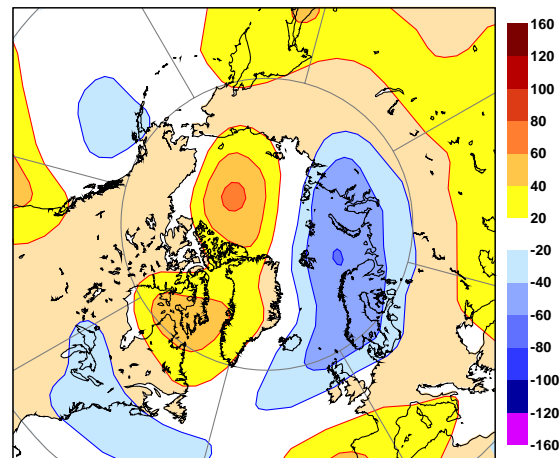
EOF1: Absolute D+2 FCE Z500 (DJF 1982-2001)



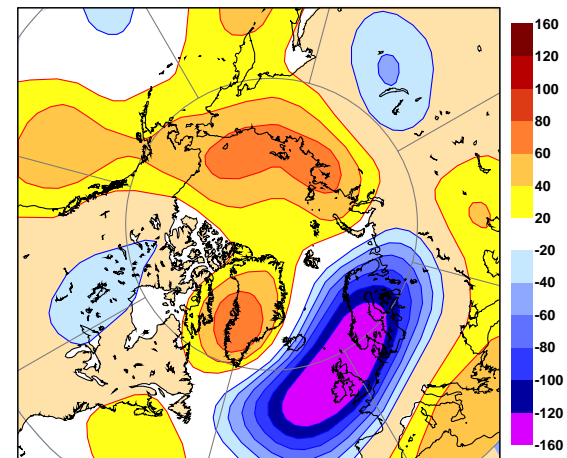
EOF2: Absolute D+2 FCE Z500 (DJF 1982-2001)



PC1-Associated Z500 Anomaly (DJF 1982-2001)

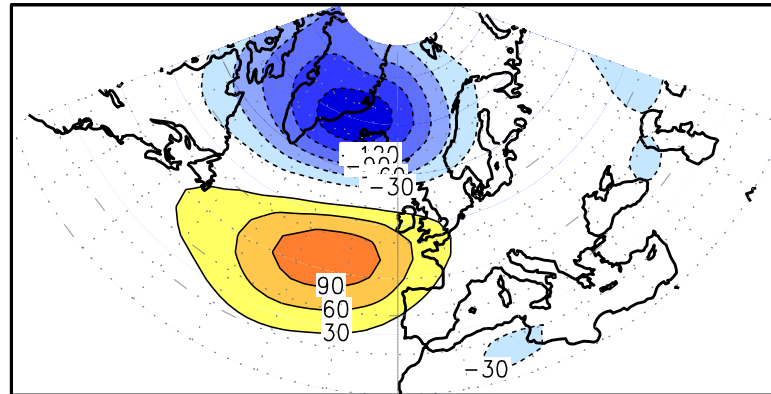


PC2-Associated Z500 Anomaly (DJF 1982-2001)

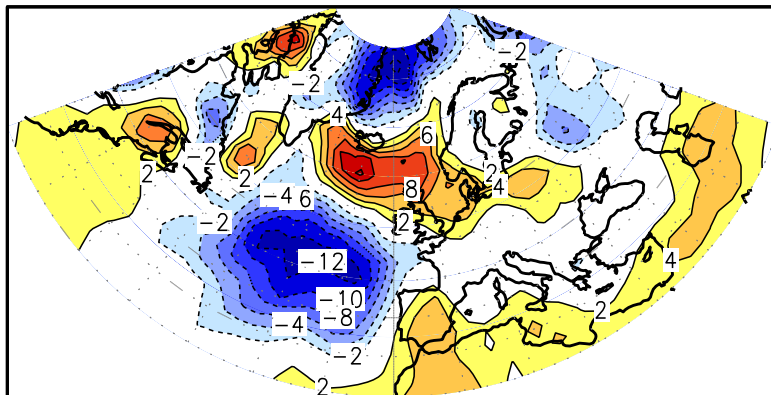


Flow-Dependent Deterministic Forecast Error

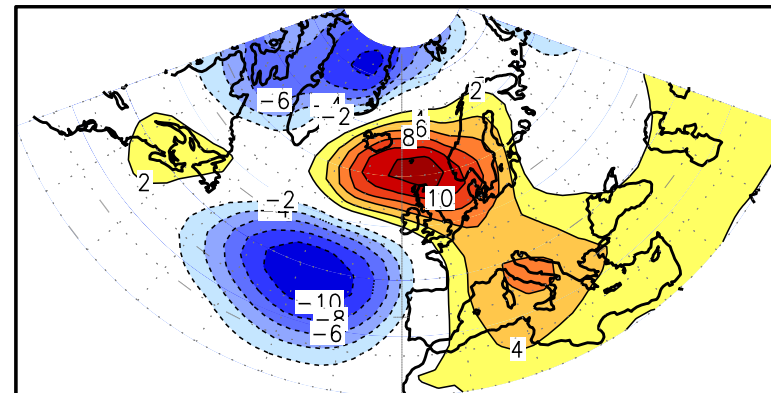
Composite Z500 (01/96–12/02)
Analysis vs NAOI



Composite Z500 (01/96–12/02)
D+5 Forecast Error vs NAOI



Composite Z500 (01/96–12/02)
D+5 EPS Spread vs NAOI



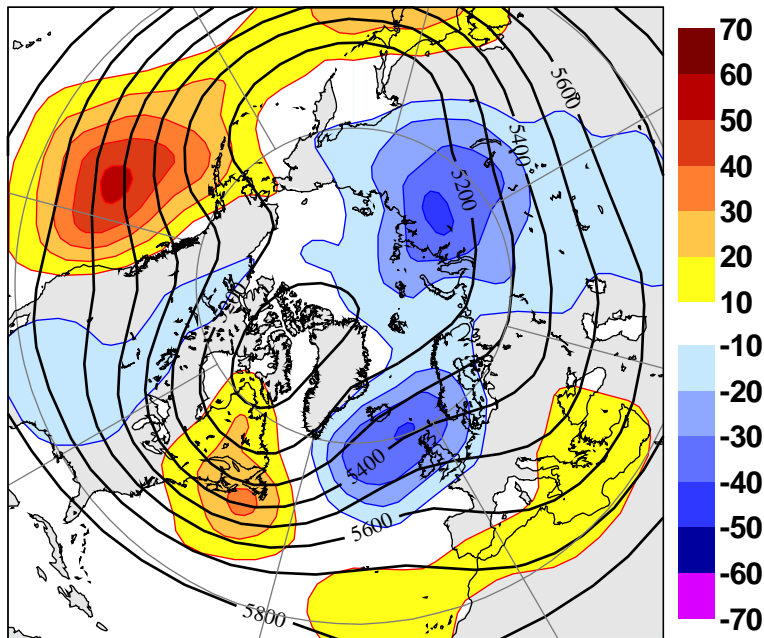
Conclusions

- **Substantial improvements in the predictive skill in polar regions**
 - Troposphere and stratosphere
 - Deterministic and probabilistic
 - Resolutions seems to be a key-element
- **Mid-latitude North Atlantic has an impact on high-latitude forecast skill (flow-dependent)**
- **Deterministic forecast error is flow-dependent**
- **EPS captures flow-dependence in the mid-latitudes (also polar regions?)**

Mean Z500 Errors at D+10 (DJF)

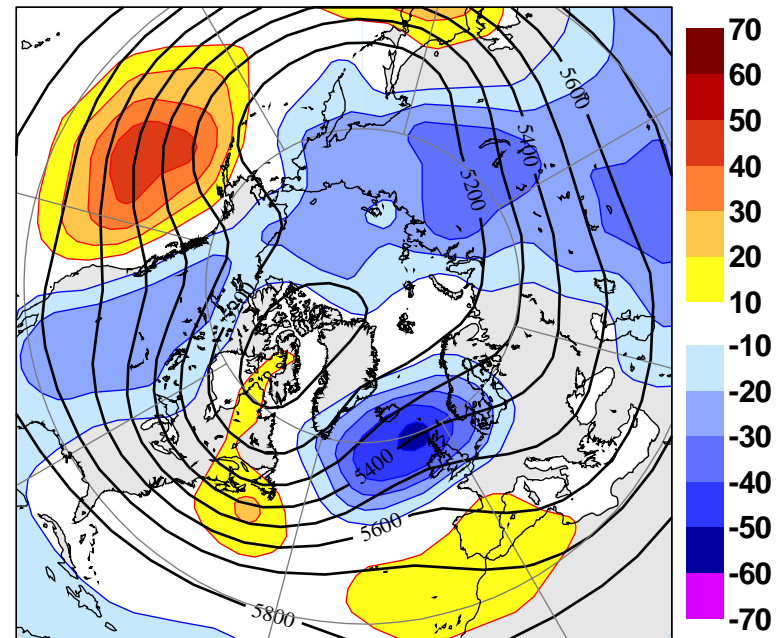
Deterministic Forecast

(a) Mean Z500 Error: FC D+10 (2001-2006 DJF)



Control Forecast

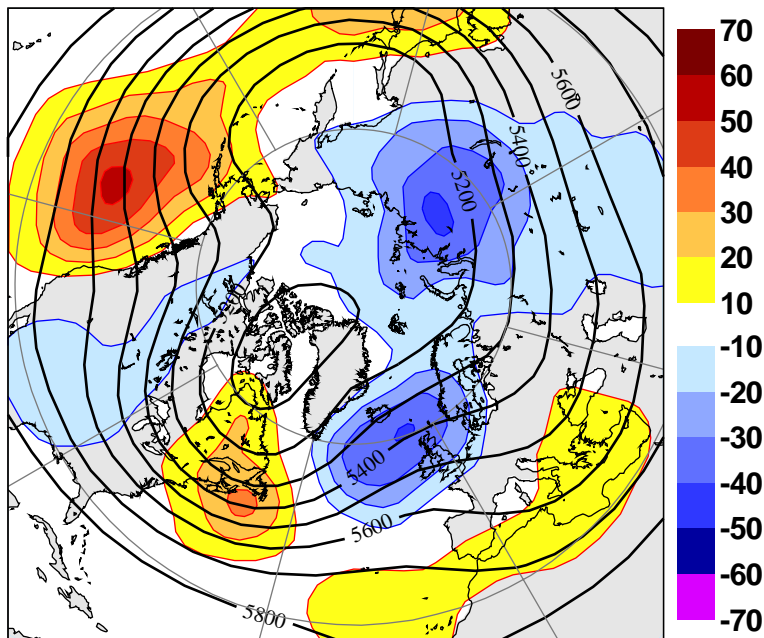
(b) Mean Z500 Error: CF D+10 (2001-2006 DJF)



Spurious Systematic Z500 Error?

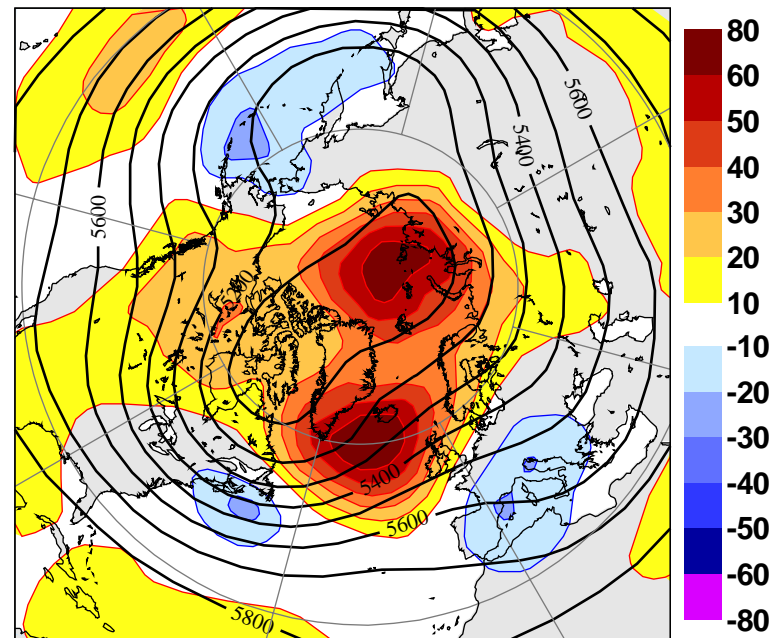
Mean D+10 Forecast Error

(DJF 2001-06)



Observed Anomaly

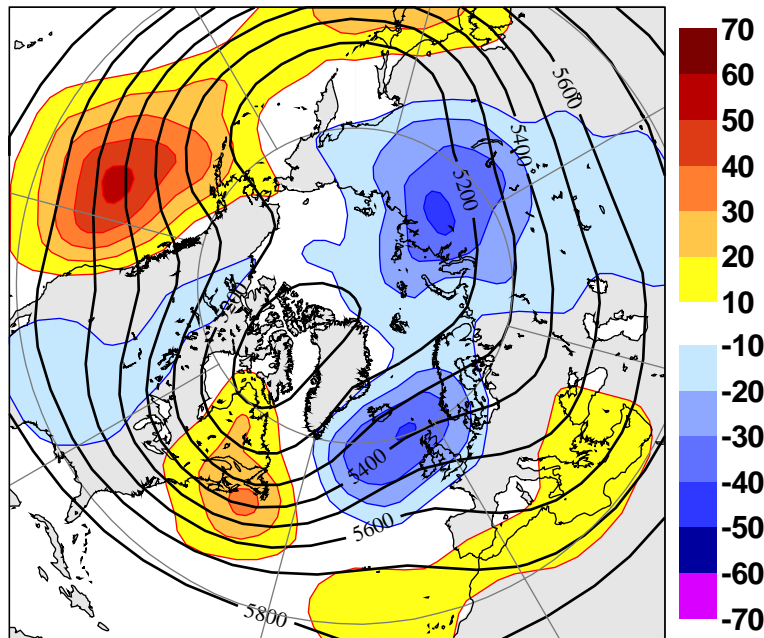
(DJF 2001-06)



Spurious Systematic Z500 Error?

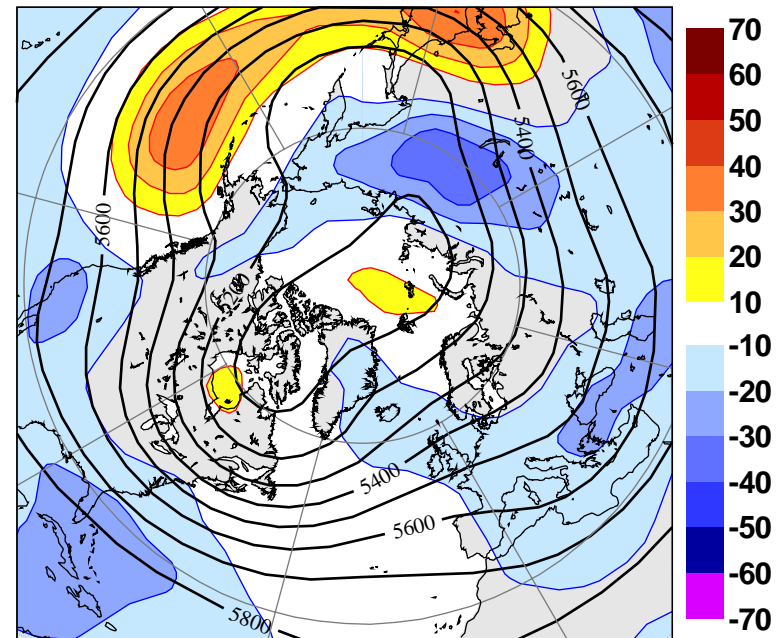
Operational D+10 FC

(a) Mean Z500 Error: FC D+10 (2001-2006 DJF)



ERA-40 D+10 FC

(a) Mean Z500 Error: ERA40-FC D+10 (1958-2001 DJF)



Conclusions

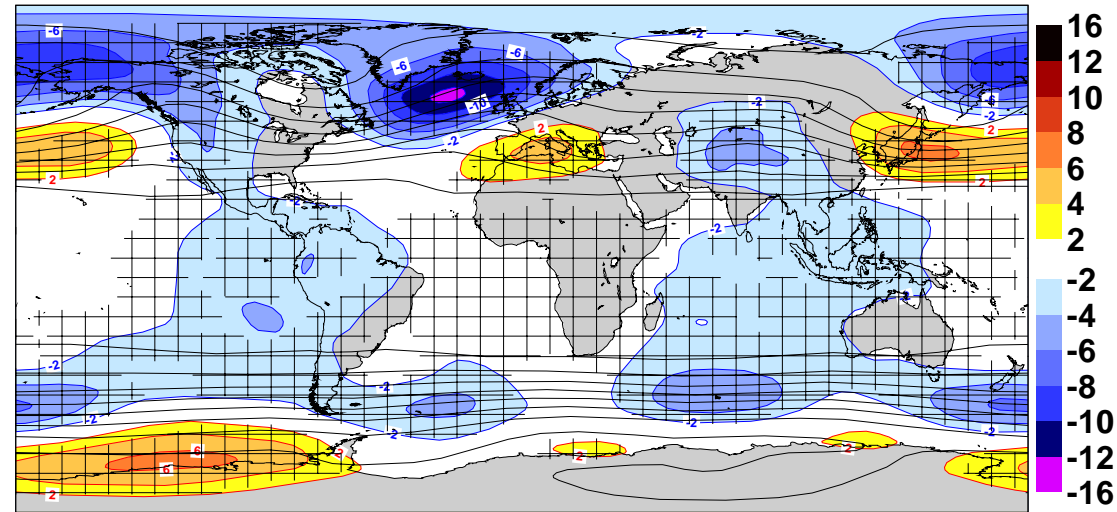
- **Systematic errors of the circulation are difficult to detect at high-latitudes (large decadal-scale variations)**
- **Loss of predictability might be misinterpreted as biases**
- **Long time series are necessary (reforecasts)**
- **ERA-40 reforecast (D+10) show rather little systematic error in polar region (NH)**
- **However, in some region systematic errors continue to grow beyond D+10...**

Seasonal Integrations

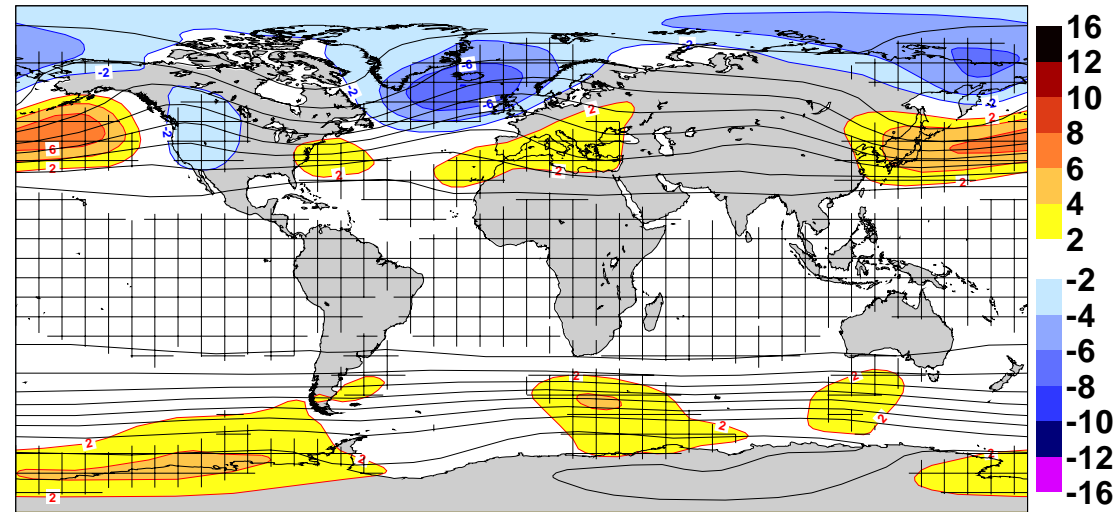
- **Atmospheric model only (different model cycles and resolutions)**
- **Lower boundary conditions: Observed SSTs (uncoupled)**
- **Initial conditions: ERA-40 and/or OD analysis**
- **One run for each of a large number of winters (e.g., 1990-2005)**

Mean Z500 Error and Horizontal Resolution (DJFM 1990-2005)

T_L95L91-OBS



T_L511L91-OBS



Extratropical Cyclones: Questions

- How well do we simulate observed characteristics of high-latitude cyclones?
- How sensitive are the results to horizontal resolution?

Extratropical Cyclones: Experiments

- **Three data sets:**
 - ERA-40/Operational analyses for verification
 - T_L95L91 run (31R1)
 - T_L159L91 run (31R1)
 - T_L255L91 run (31R1)
 - T_L511L91 run (31R1)
- **DJFM 1990-2005 (forecasts start 1st November)**
- **6-hourly MSLP interpolated to a common 2.5x2.5 deg grid**

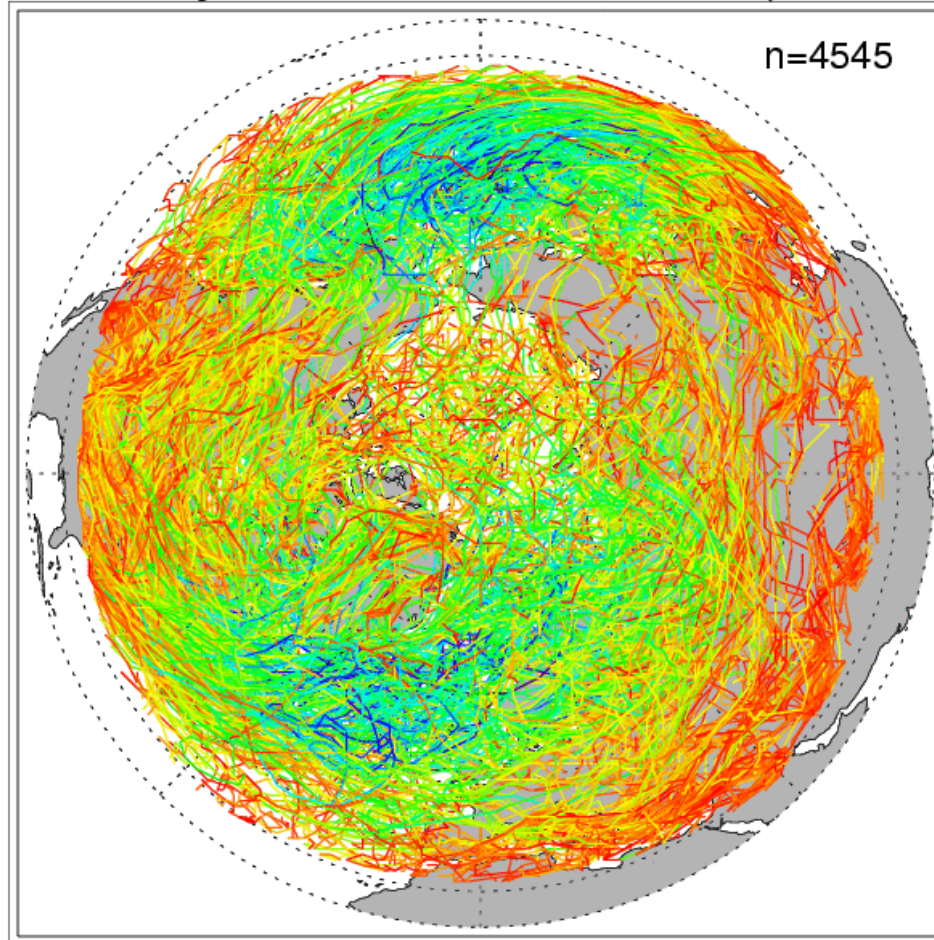
Description up to T255 in Jung et al. (2006), to appear in QJ

Tracking Software

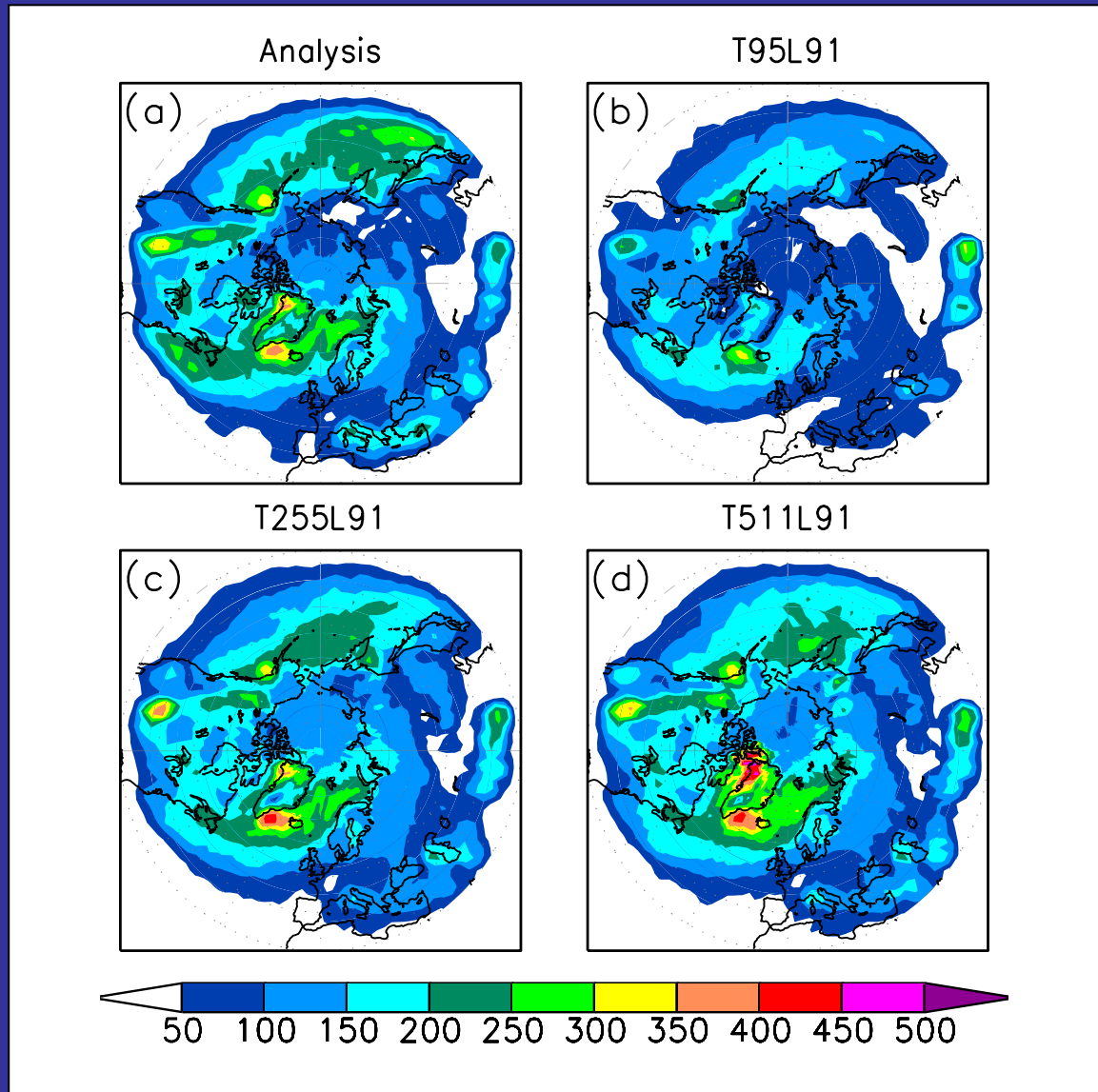
- **Strategy: Searching for and tracking local minima in MSLP fields**
- **High temporal resolution required (6-hourly data)**
- **Data have been interpolated to 1-hourly data for tracking**
- **The accuracy of the software is very high (verified against manually tracked systems)!**
- **The software has been developed by Sergey Gulev and co-workers**

Extratropical Cyclone Tracks and Pressure

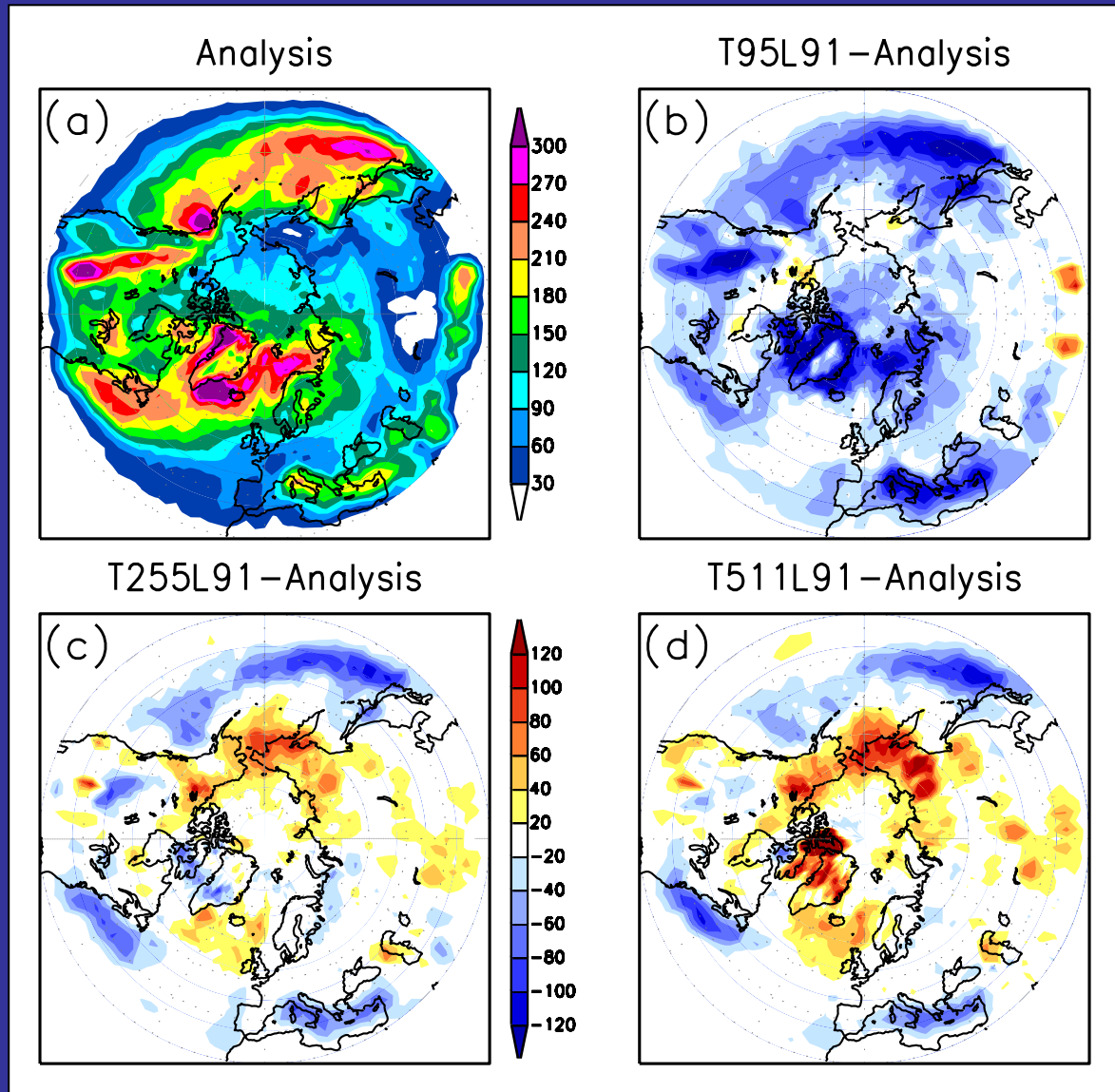
ERA-40 Cyclones DJFM 1995-2000 (T159L60)



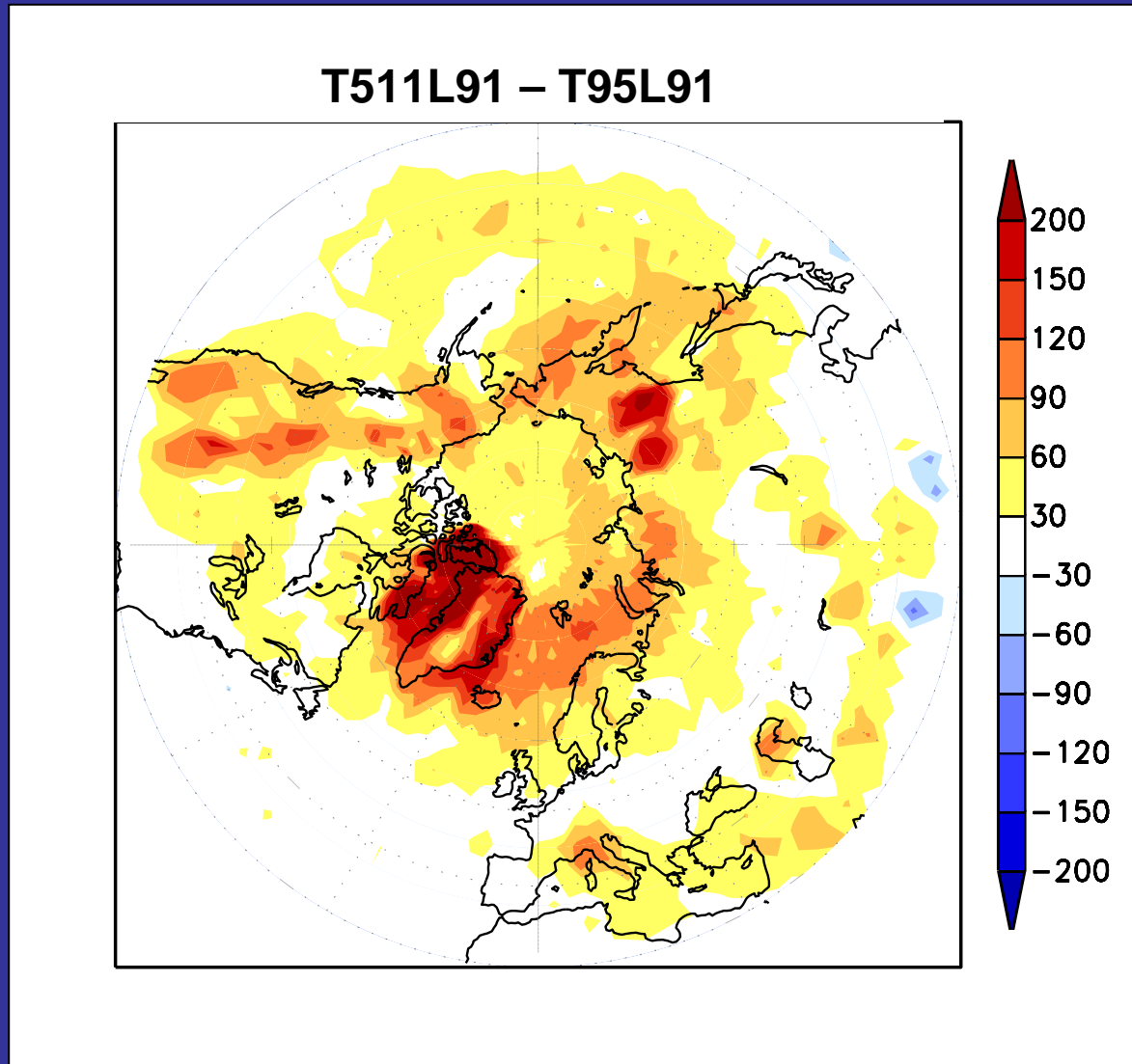
Number of Extratropical Cyclones (1990-2005)



Number of Extratropical Cyclones (1990-2005)



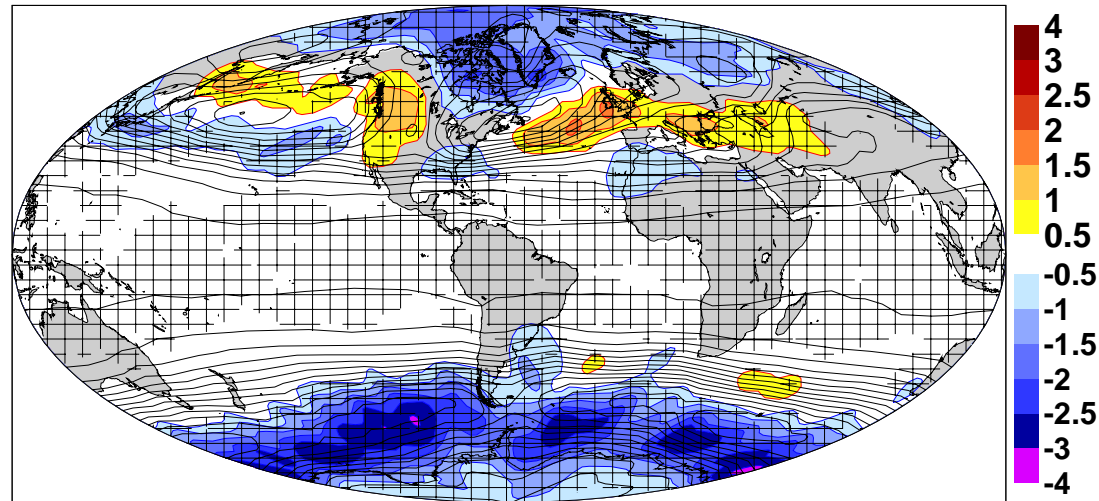
Influence of Horizontal Resolution on the Number of Extratropical Cyclones (1990-2005)



Synoptic Activity and Horizontal Resolution (DJFM 1990-2005)

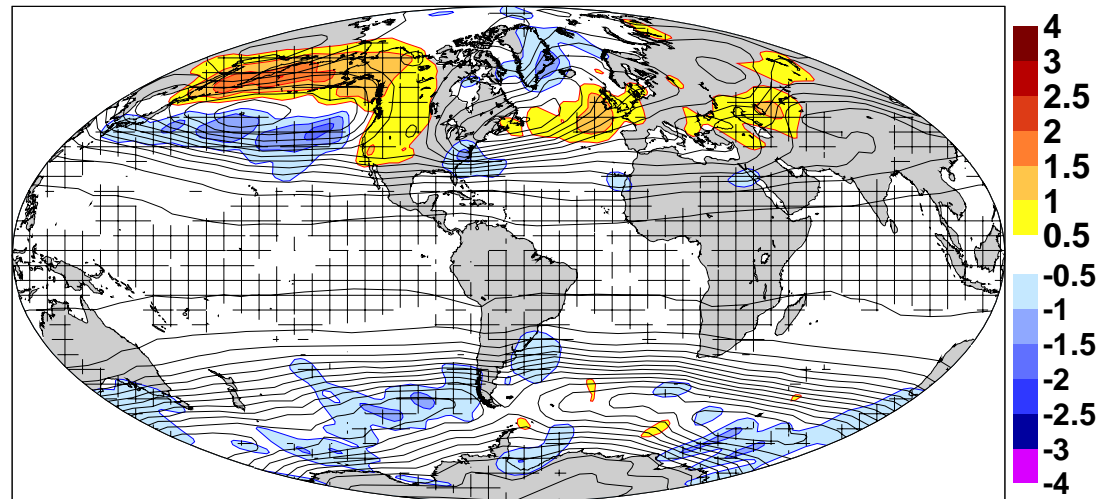
T_{L95L91}
-ERA40

Synoptic Z500 Activity: Difference esm0-er40 (12-3 1990-2005)



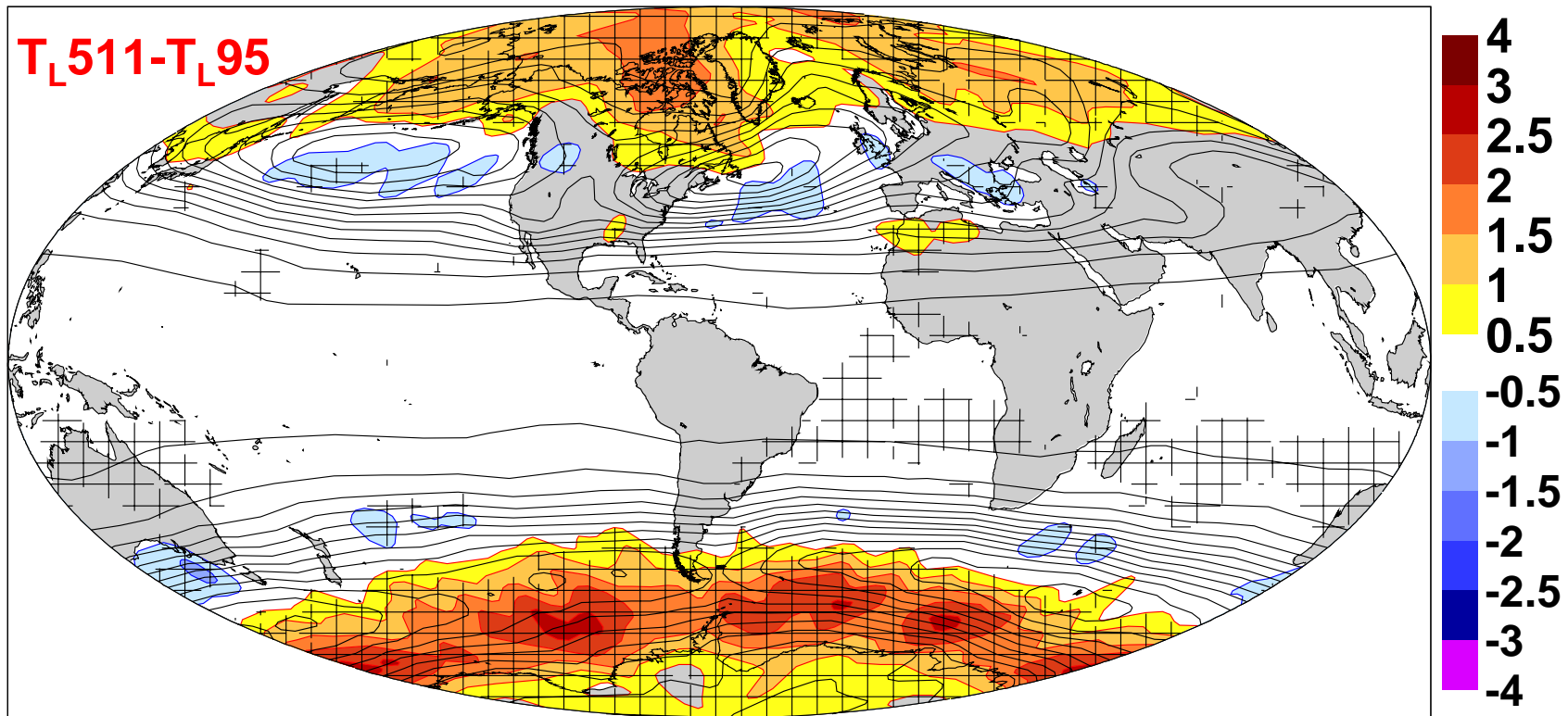
$T_{L511L91}$
-ERA40

Synoptic Z500 Activity: Difference eslx-er40 (12-3 1990-2005)

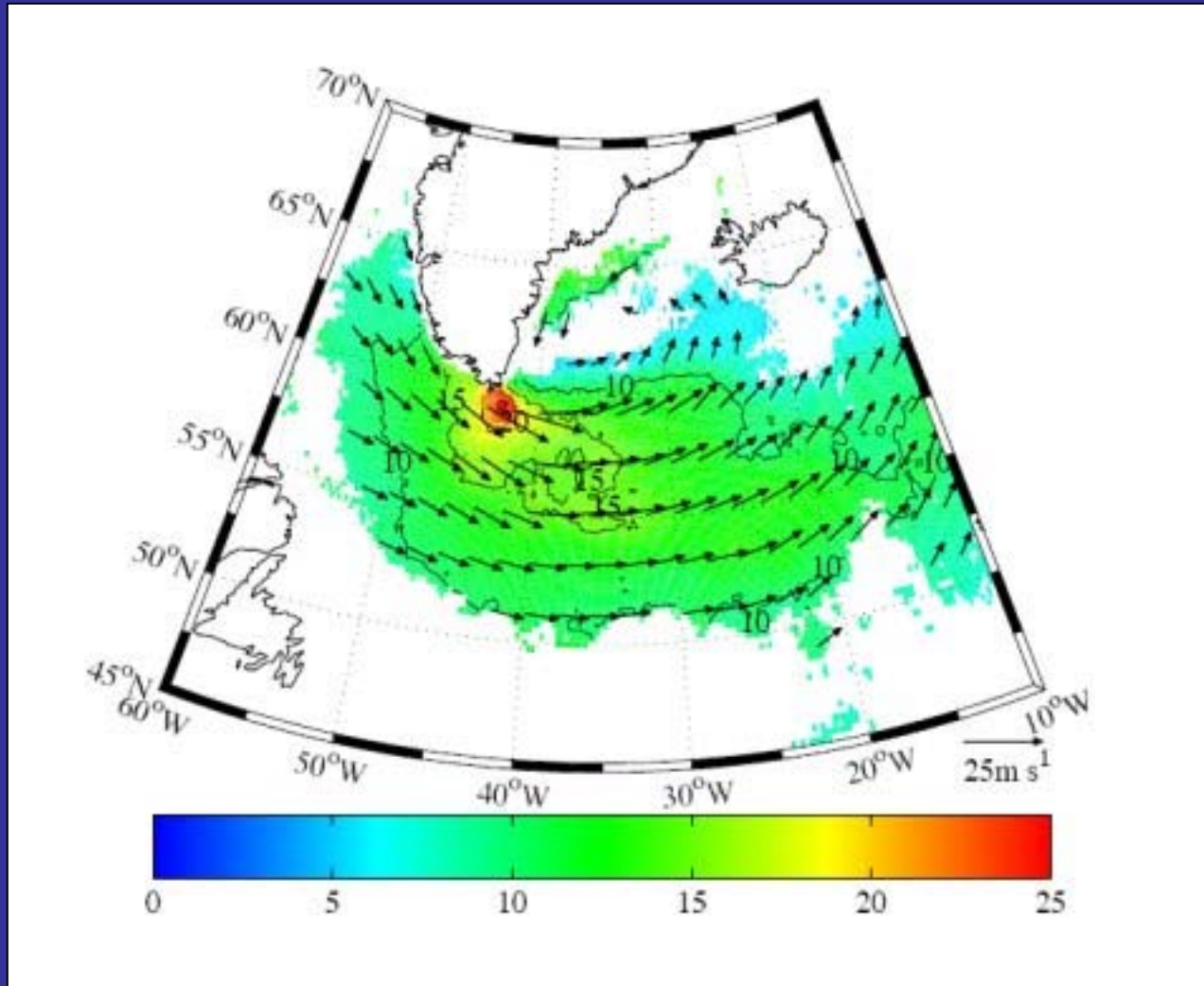


Synoptic Activity and Horizontal Resolution (1990-2005)

Synoptic Z500 Activity: Difference eslx-esm0 (12-3 1990-2005)



The Greenland Tip Jet Events

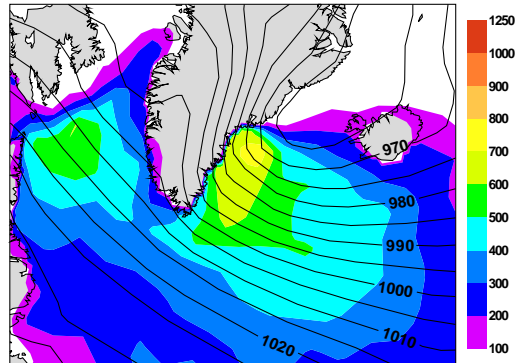


Moore and Renfrew (2005)

Greenland Tip Jet Events: D+1 Forecasts at Various Resolutions

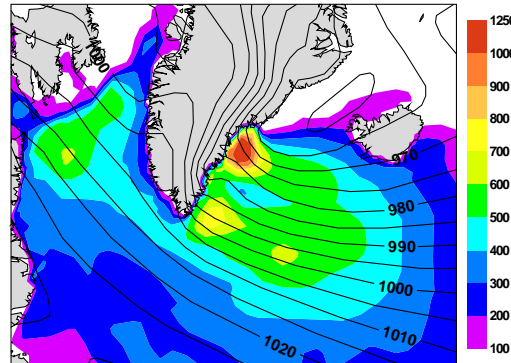
T_L 95L91

(a) SLP and Turbulent Heat Fluxes: 20041226 12z FC+24h (T95)



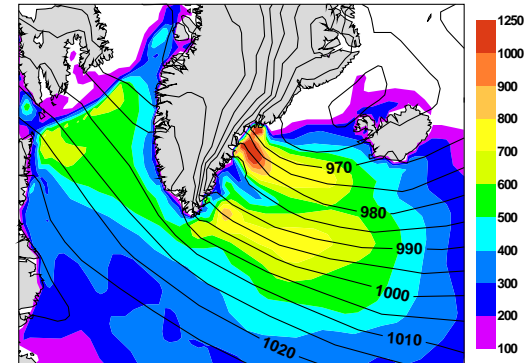
T_L 255L91

(b) SLP and Turbulent Heat Fluxes: 20041226 12z FC+24h (T255)

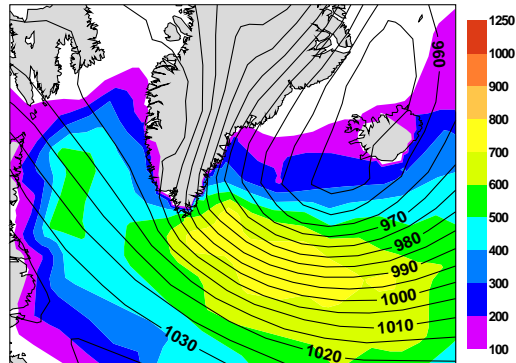


T_L 799L91

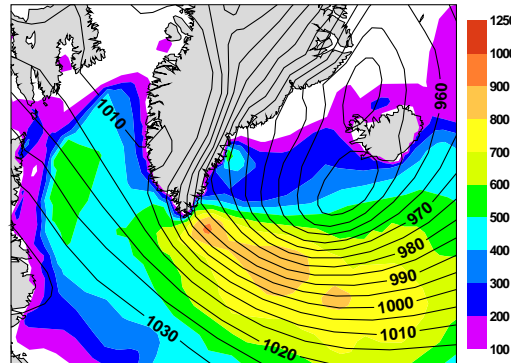
(c) SLP and Turbulent Heat Fluxes: 20041226 12z FC+24h (T799)



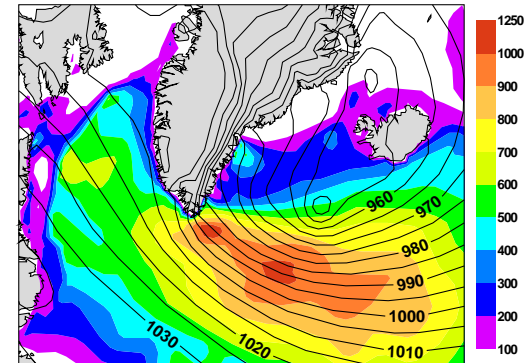
(d) SLP and Turbulent Heat Fluxes: 20050116 12z FC+24h (T95)



(e) SLP and Turbulent Heat Fluxes: 20050116 12z FC+24h (T255)



(f) SLP and Turbulent Heat Fluxes: 20050116 12z FC+24h (T799)

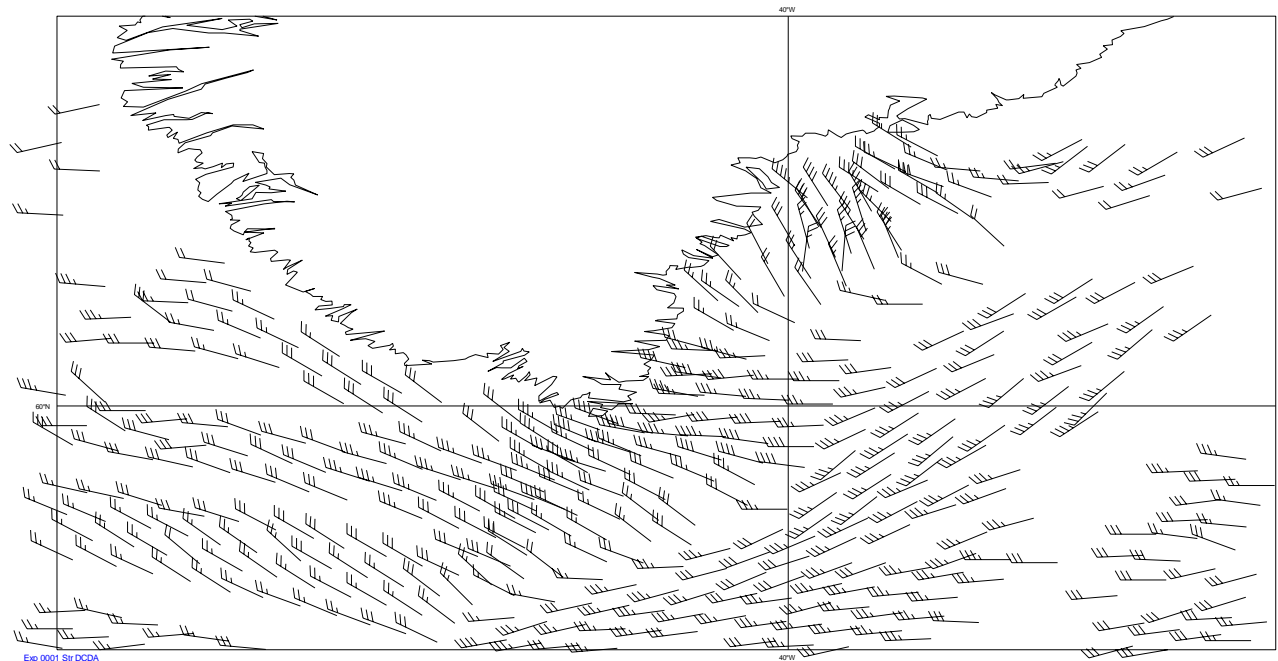
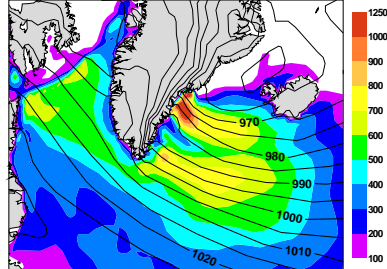


Greenland Tip Jet Events: QuikSCAT Winds

T_L799L60

50km-QSCAT scatterometer data coverage
4D-Var de-aliased winds for 2004122700

(c) SLP and Turbulent Heat Fluxes: 20041226 12z FC+24h (T799)



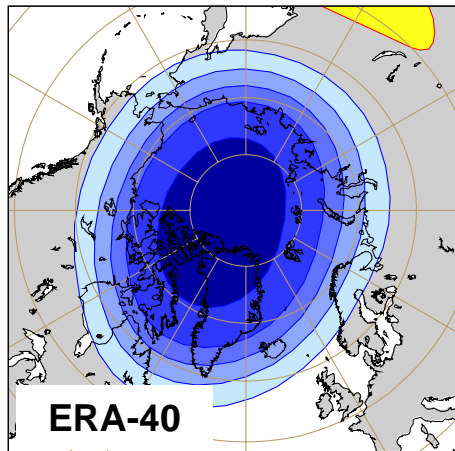
Exp 0001 Str DCCA

Courtesy of Hans Hersbach

Leading EOFs: Z50 Anomalies

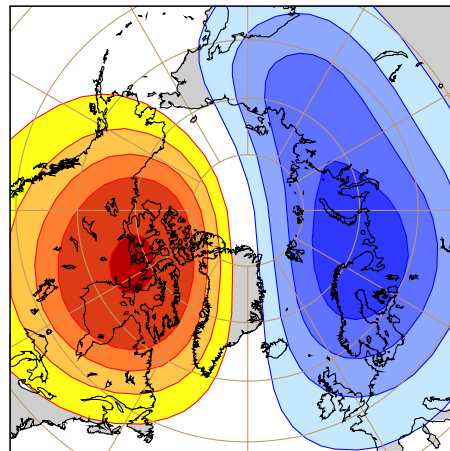
53.0%

EOF1 53%: Z50 Anomalies er40 (12-3 1962-2001)



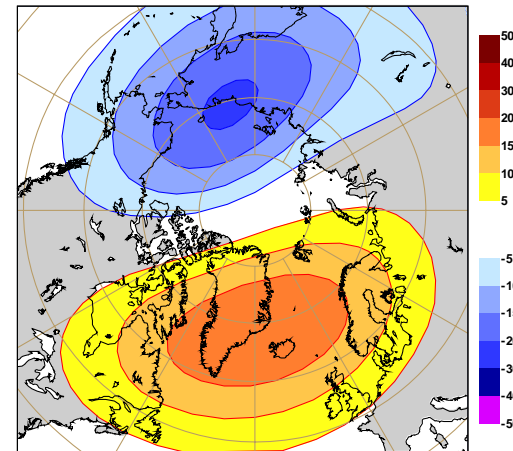
17.3%

EOF2 17.3%: Z50 Anomalies er40 (12-3 1962-2001)



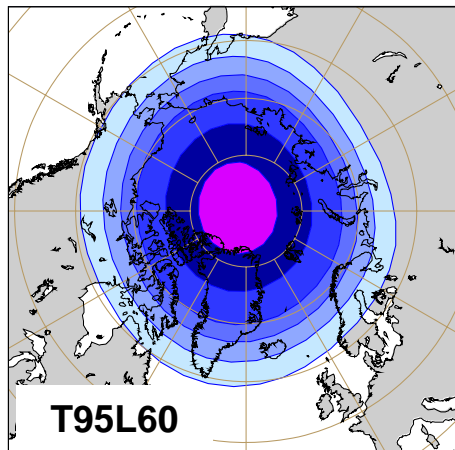
8.8%

EOF3 8.84%: Z50 Anomalies er40 (12-3 1962-2001)



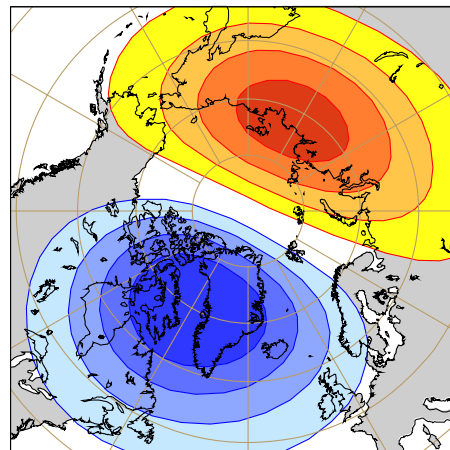
62.4%

EOF1 62.4%: Z50 Anomalies eqzy (12-3 1962-2001)



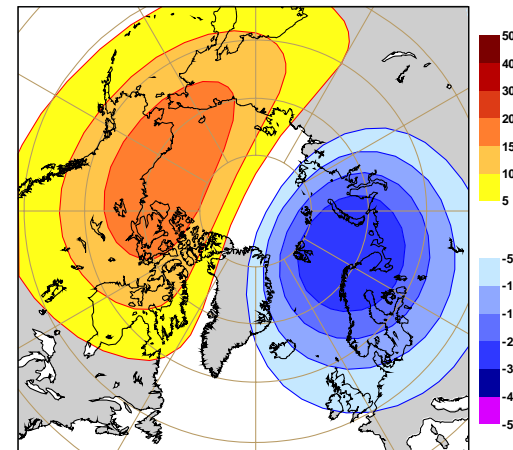
12.3%

EOF2 12.3%: Z50 Anomalies eqzy (12-3 1962-2001)



10.7%

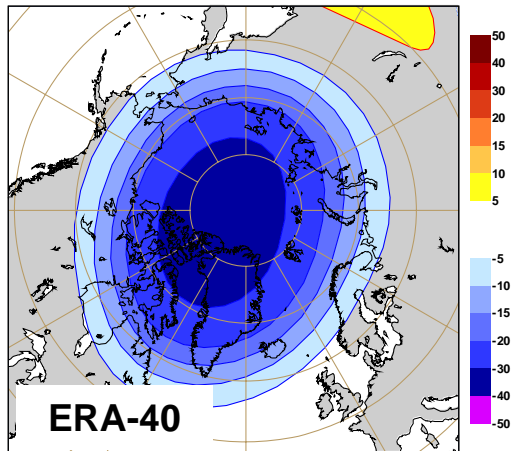
EOF3 10.7%: Z50 Anomalies eqzy (12-3 1962-2001)



Leading EOFs: Z50 Anomalies

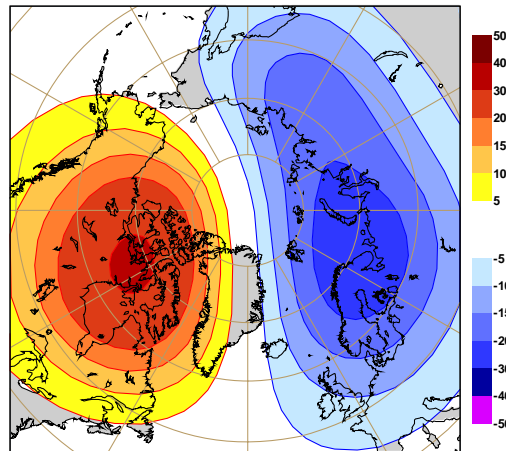
53.0%

EOF1 53%: Z50 Anomalies er40 (12-3 1962-2001)



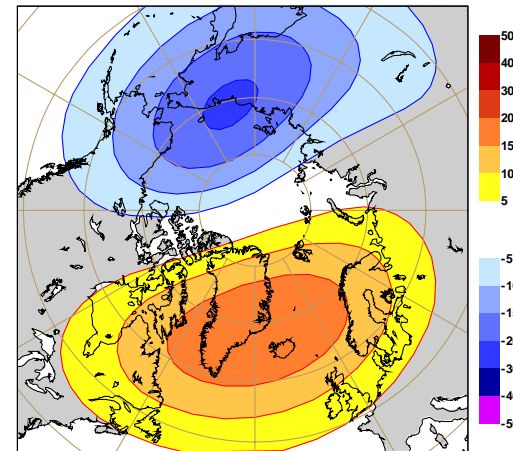
17.3%

EOF2 17.3%: Z50 Anomalies er40 (12-3 1962-2001)



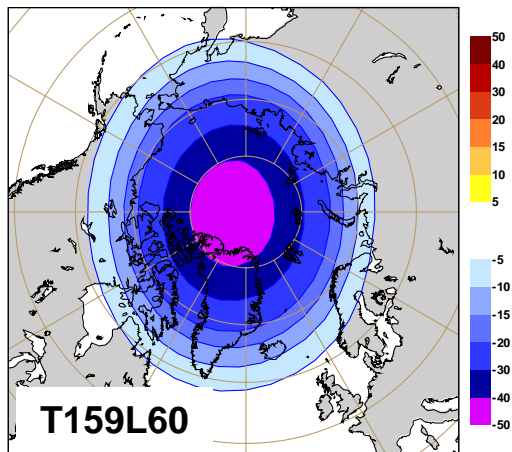
8.8%

EOF3 8.84%: Z50 Anomalies er40 (12-3 1962-2001)



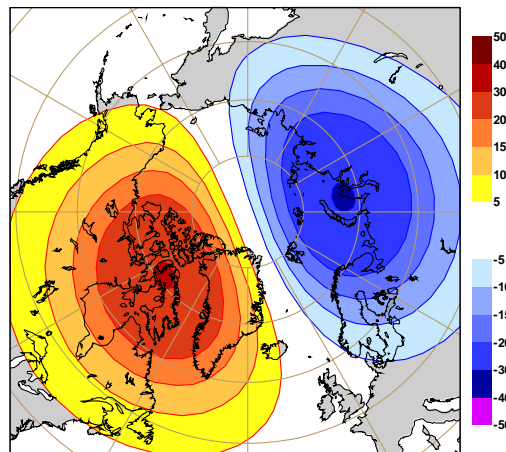
58.4%

EOF1 58.4%: Z50 Anomalies em3i (12-3 1962-2001)



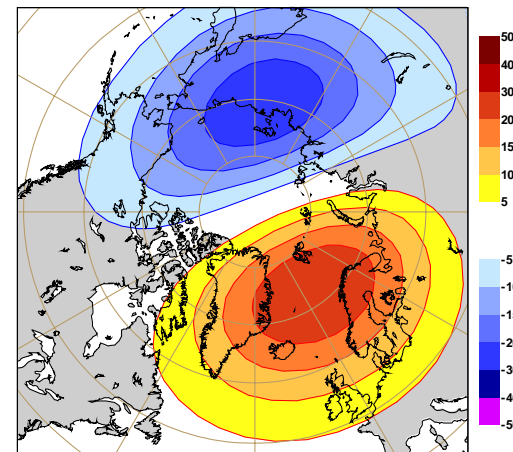
15.6%

EOF2 15.6%: Z50 Anomalies em3i (12-3 1962-2001)

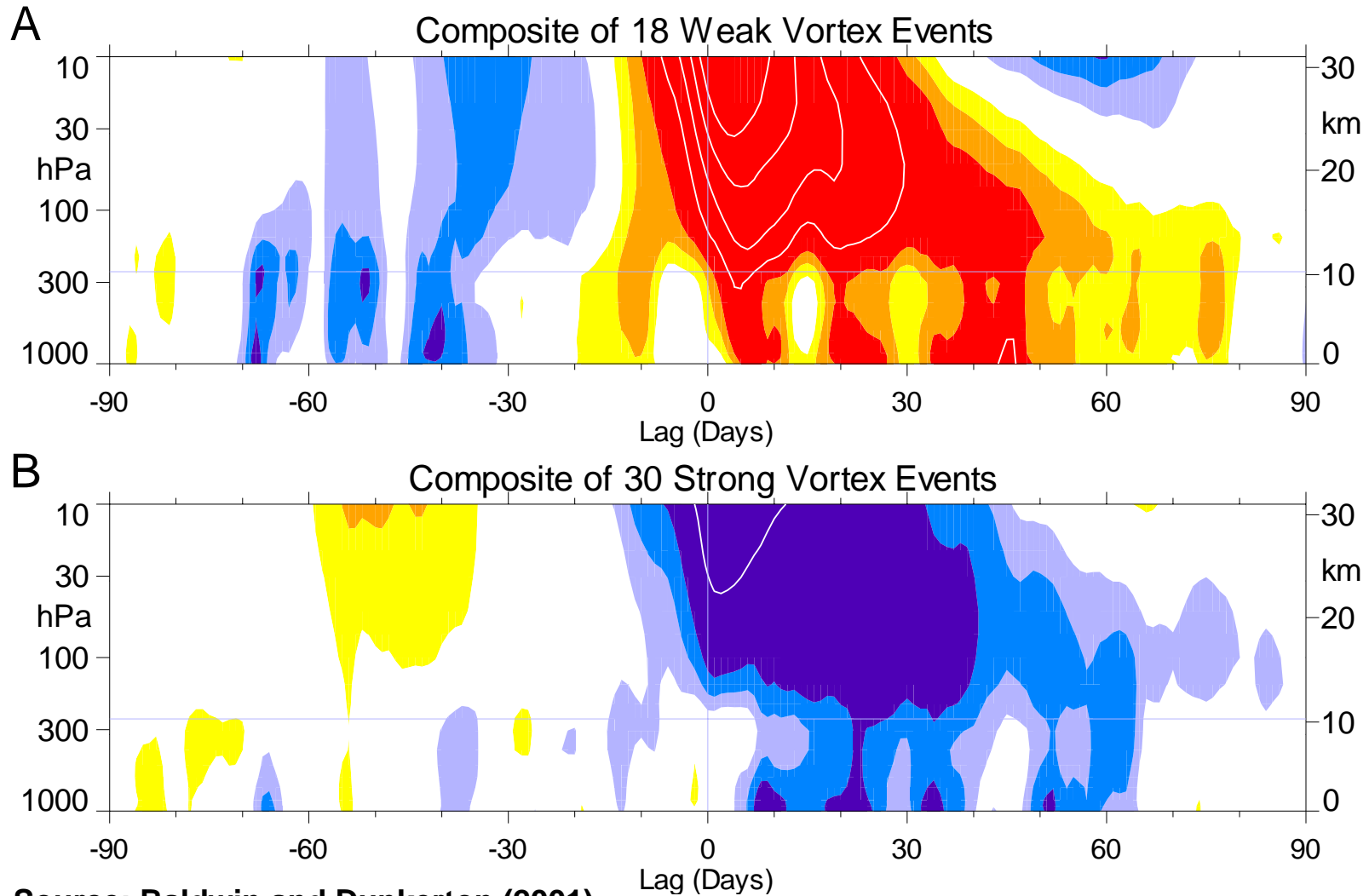


10.2%

EOF3 10.2%: Z50 Anomalies em3i (12-3 1962-2001)



The Stratosphere-Troposphere Link



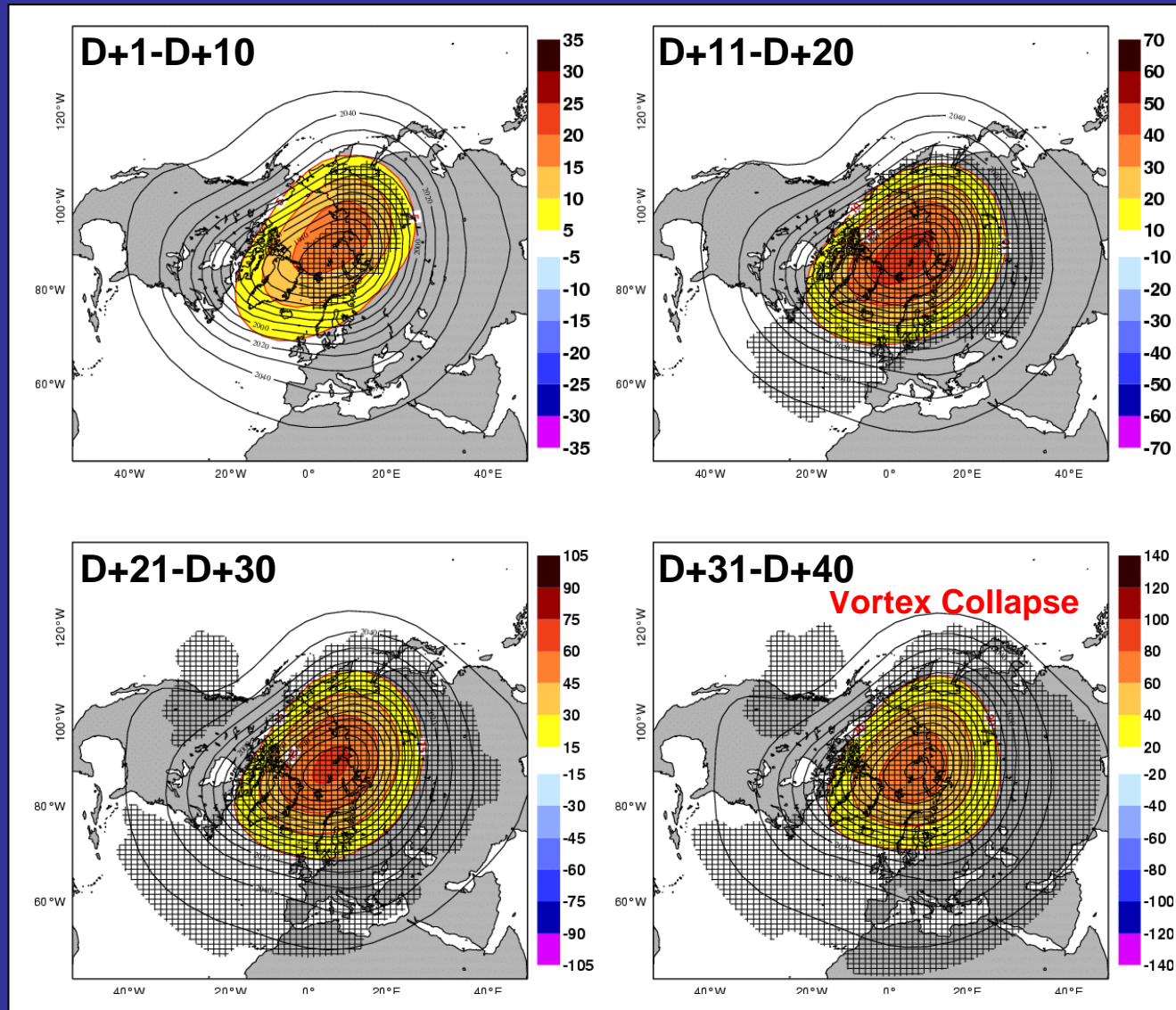
Source: Baldwin and Dunkerton (2001)

Methodology

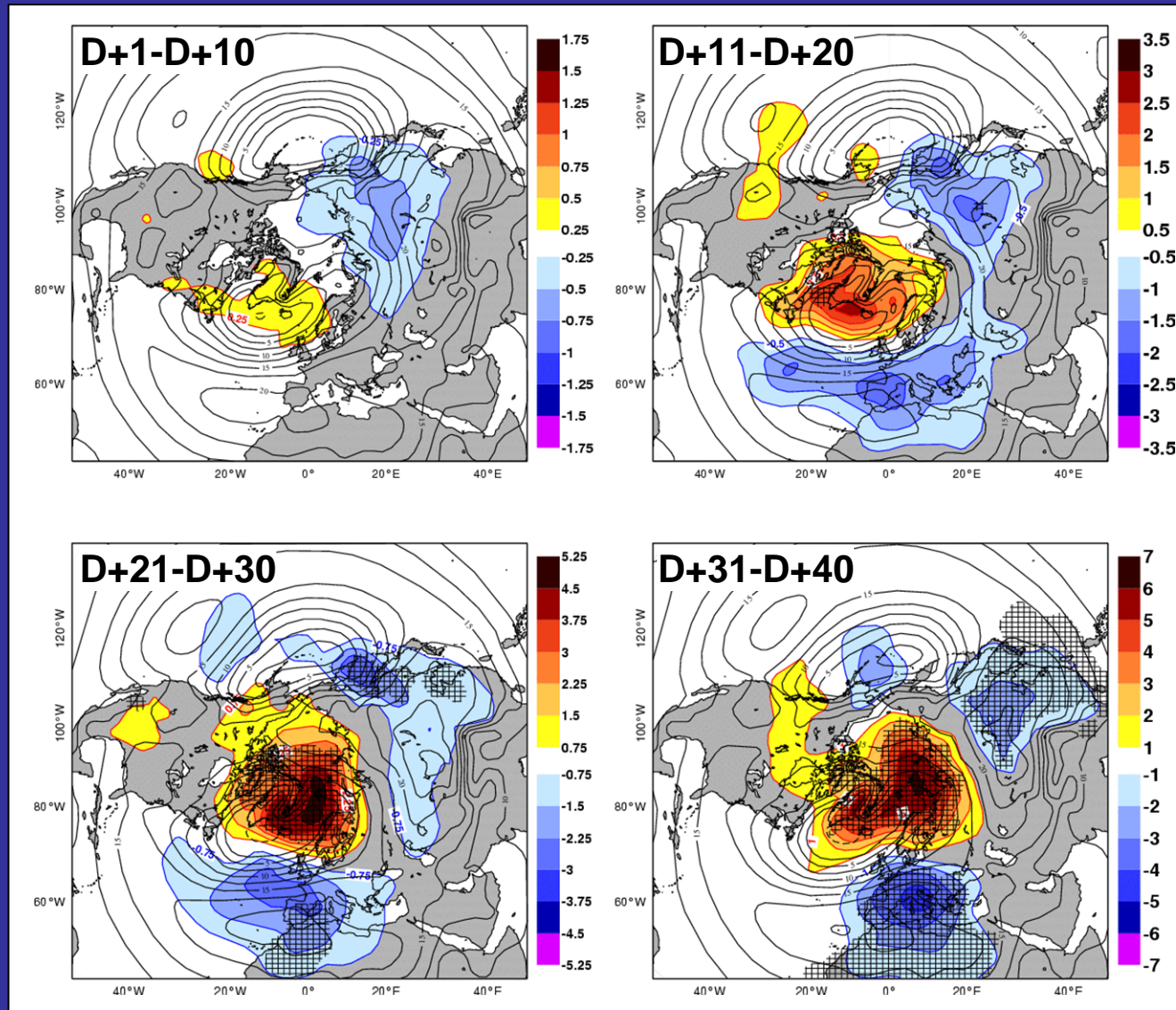
$$\dot{\mathbf{x}} = \mathbf{IFS}(\mathbf{x}_0) \pm \mathbf{F}$$

- **F is the composite optimal forcing of the polar vortex (adjoint, 18 cases)**
- **F is applied in the stratosphere only (>150 hPa)**
- **3 40-day forecasts for every winter (1982-2001)**
- **Control & Control \pm F**
- **T_L95L60 (cycle 28r1)**

Stratospheric Response (50hPa)



Z1000 Response (Weak-CNTL)

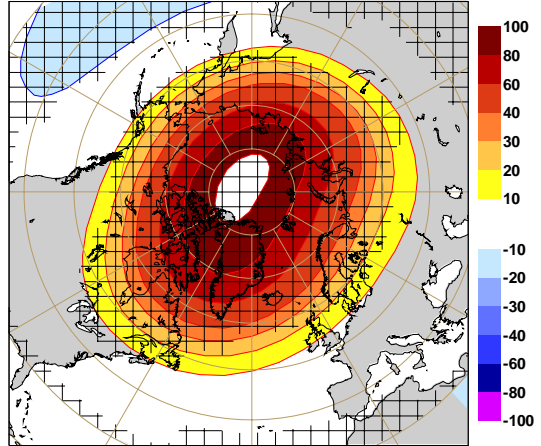


Strong Vortex Composites (ERA-40)

10 hPa

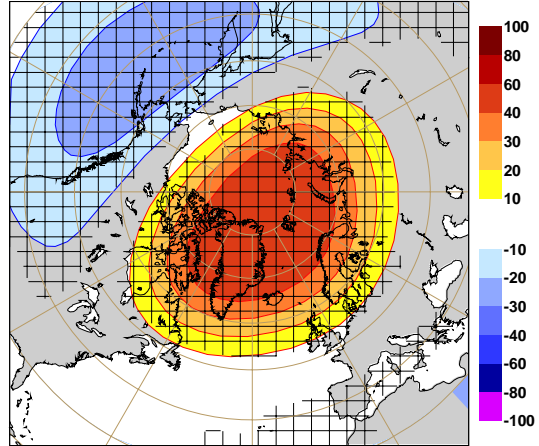
D+1 to D+20

(a) Weak Vortex Composite (D+1 to D+20)
Z10 Anomalies er40 (12-3 1962-2001)



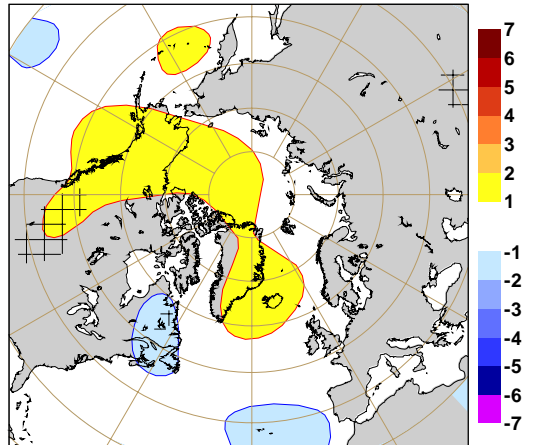
D+21 to D+40

(b) Weak Vortex Composite (D+21 to D+40)
Z10 Anomalies er40 (12-3 1962-2001)

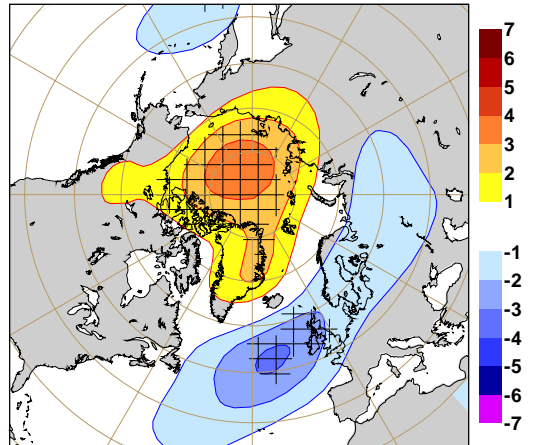


1000 hPa

(c) Weak Vortex Composite (D+1 to D+20)
Z1000 Anomalies er40 (12-3 1962-2001)



(d) Weak Vortex Composite (D+21 to D+40)
Z1000 Anomalies er40 (12-3 1962-2001)

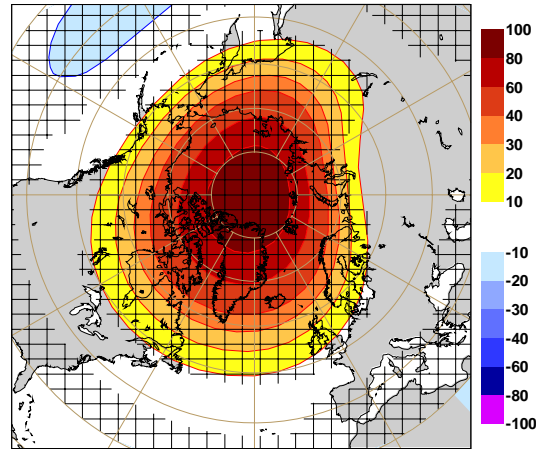


Strong Vortex Composites (T_L95L91)

10 hPa

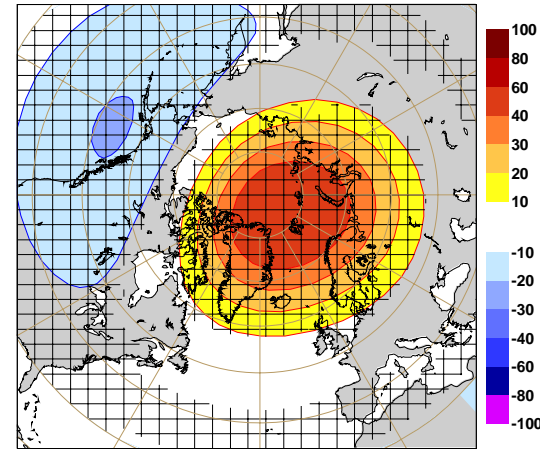
D+1 to D+20

(a) Weak Vortex Composite (D+1 to D+20)
Z10 Anomalies eqz8 (12-3 1962-2001)



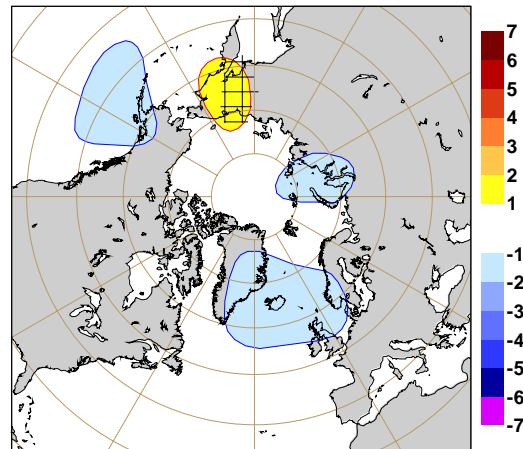
D+21 to D+40

(b) Weak Vortex Composite (D+21 to D+40)
Z10 Anomalies eqz8 (12-3 1962-2001)

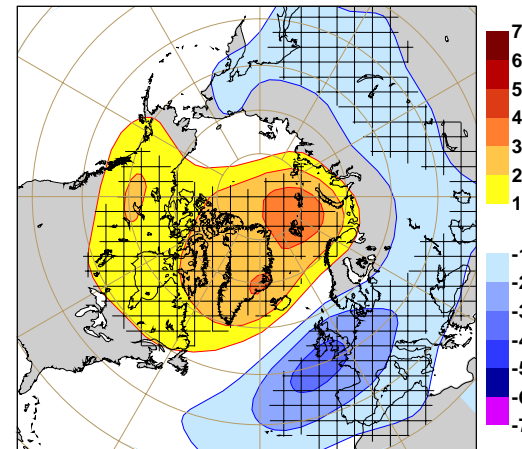


1000 hPa

(c) Weak Vortex Composite (D+1 to D+20)
Z1000 Anomalies eqz8 (12-3 1962-2001)



(d) Weak Vortex Composite (D+21 to D+40)
Z1000 Anomalies eqz8 (12-3 1962-2001)

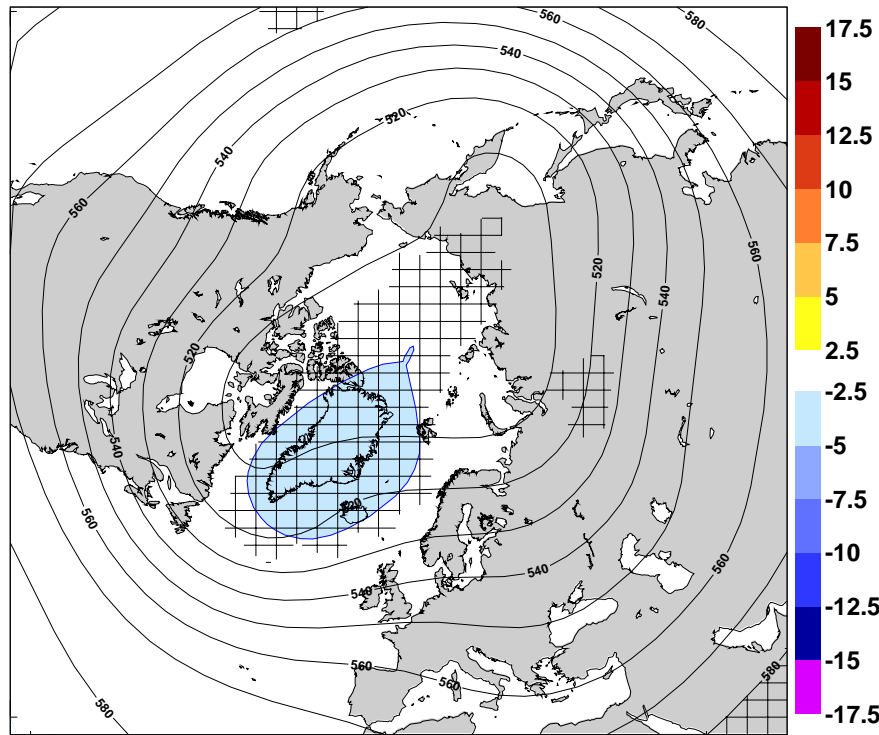


Sensitivity to Vertical Resolution

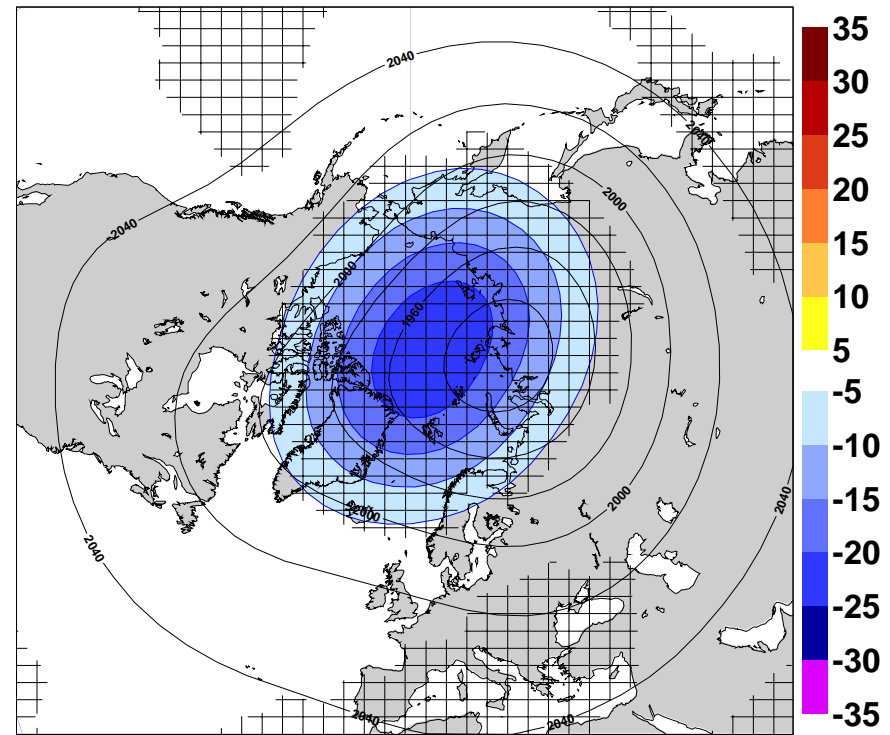
- Two different resolutions (L62 and L91)
- Same resolution up to 150hPa.
- **L91:**
 - About 45 levels in the stratosphere
 - Highest level at 0.01 hPa
- **L62:**
 - About 15 levels in the stratosphere
 - Highest level at 5 hPa
- All runs at T_L95
- DJFM 1962-2001 (starts on 1st October)

Influence of Vertical Resolution (L62-L91)

Troposphere

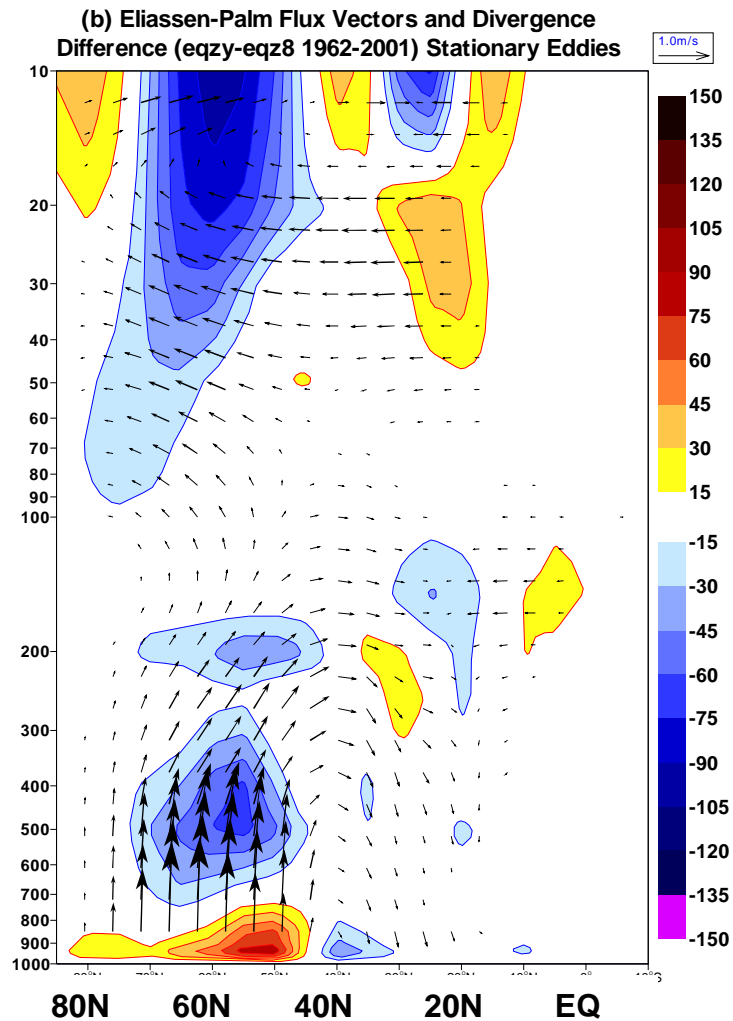


Stratosphere

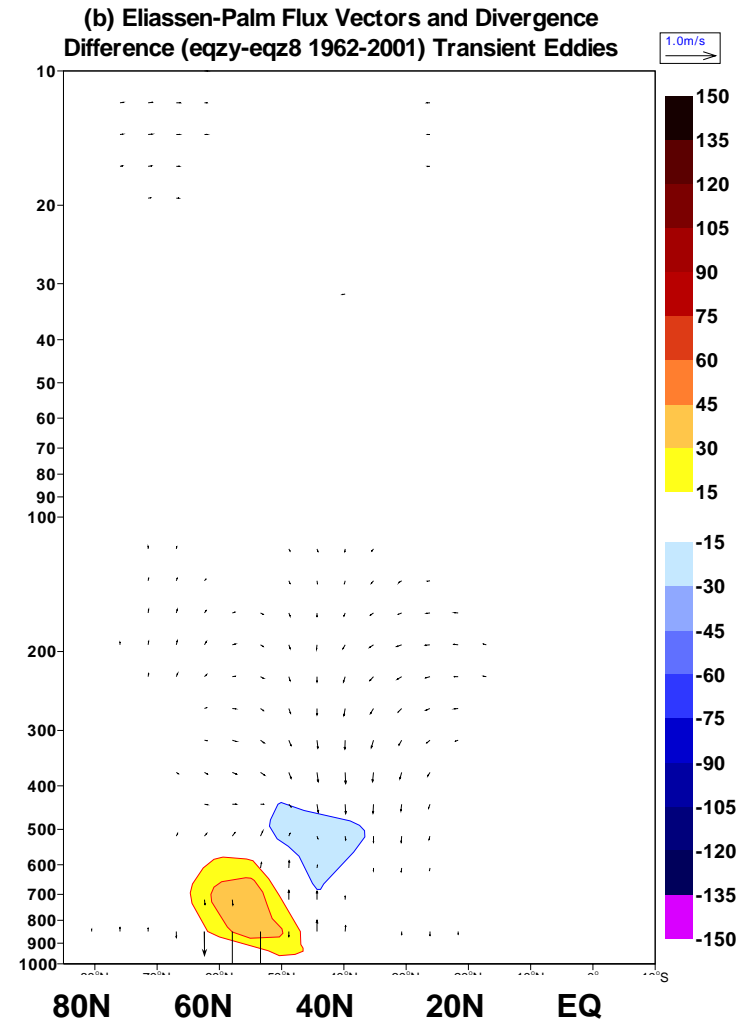


Influence of Vertical Resolution (L62-L91)

Stationary Waves



Transient Waves



Conclusions

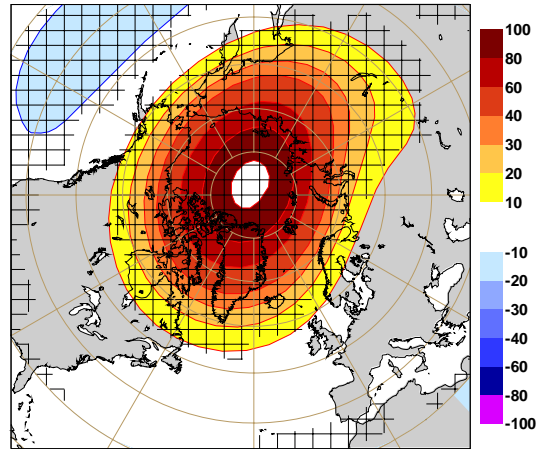
- Substantial improvements of the model climate at very high resolution (e.g, westerly wind bias).
- This is particularly true for synoptic-scale systems in high-latitudes.
- More realistic simulation of the stratospheric eigenstructure.
- Vertical resolution primarily influences stationary waves.
- “Downward propagation” is captured by the ECMWF model (even at T_L95L62).

Strong Vortex Composites (T_L95L62)

10 hPa

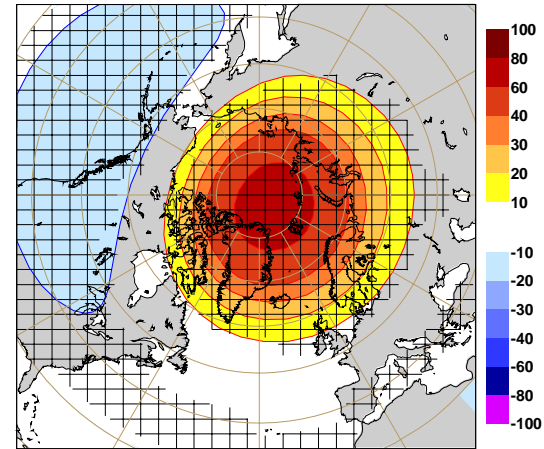
D+1 to D+20

(a) Weak Vortex Composite (D+1 to D+20)
Z10 Anomalies eqzy (12-3 1962-2001)



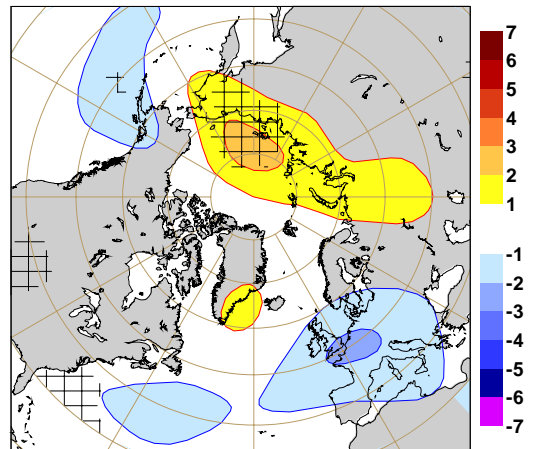
D+21 to D+40

(b) Weak Vortex Composite (D+21 to D+40)
Z10 Anomalies eqzy (12-3 1962-2001)

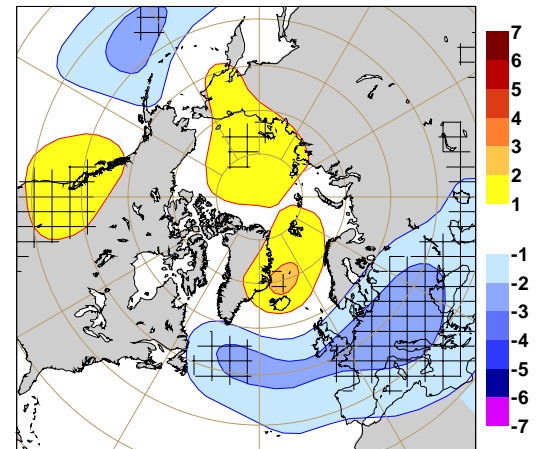


1000 hPa

(c) Weak Vortex Composite (D+1 to D+20)
Z1000 Anomalies eqzy (12-3 1962-2001)

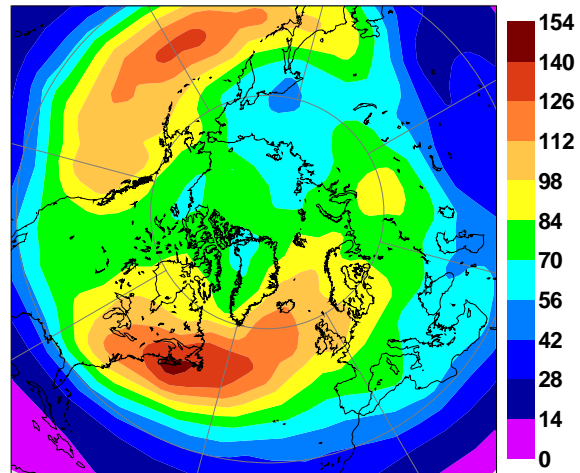


(d) Weak Vortex Composite (D+21 to D+40)
Z1000 Anomalies eqzy (12-3 1962-2001)

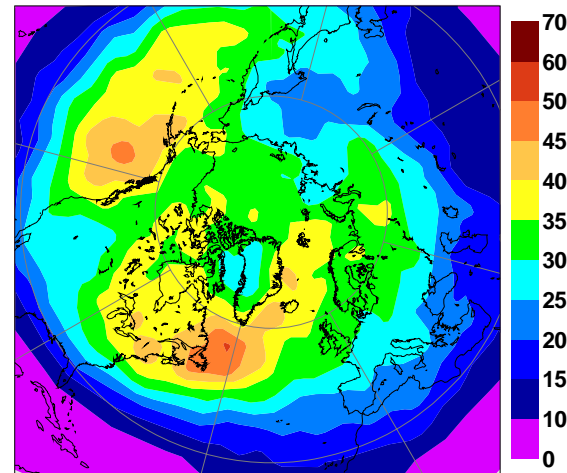


STD of Forecast Error: D+2.5 Z500 Tendency (2-8 days)

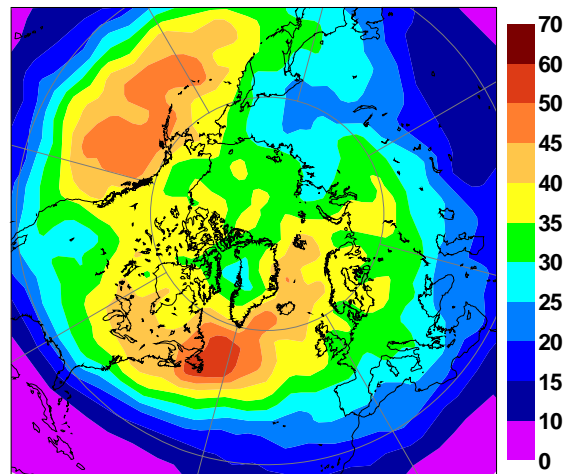
(a) STDEV: Z500 Tendency Analyses (2001-2006 DJF)



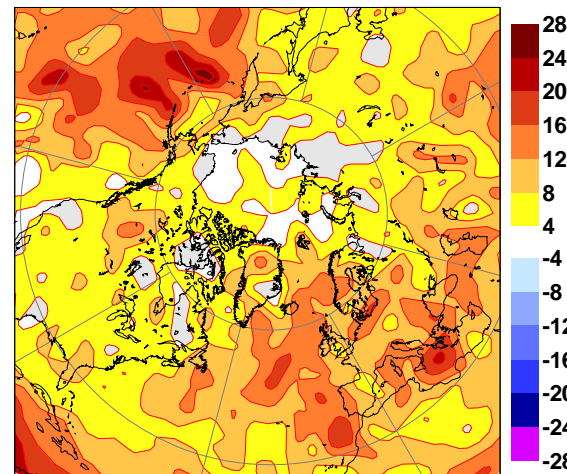
(b) STDEV: D+3-D+2 Z500 FC Error (2001-2006 DJF)



(c) STDEV: D+3-D+2 Z500 CF Error (2001-2006 DJF)



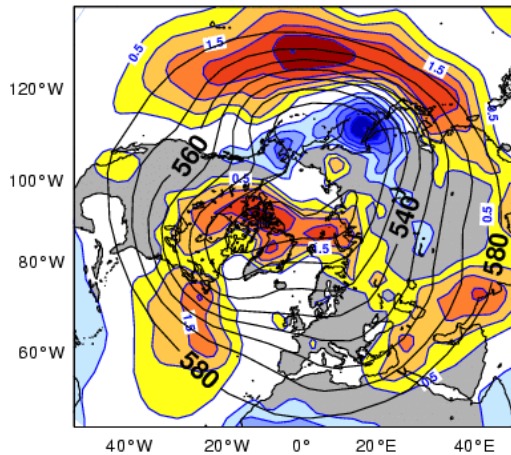
(d) Difference: (c)-(b)



Evolution of D+3 Systematic Z500 Errors

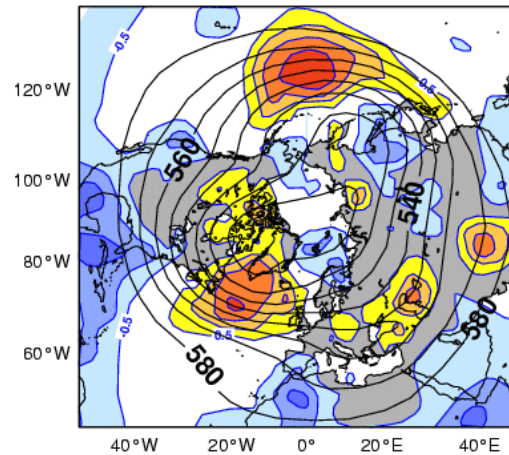
1986-1988

(a) Z500 Difference D+3 FC-Analysis (DJFM 1986-1988)



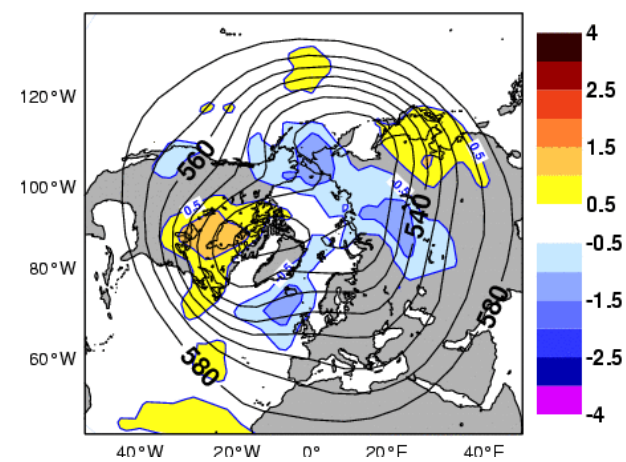
1993-1995

(b) Z500 Difference D+3 FC-Analysis (DJFM 1993-1995)



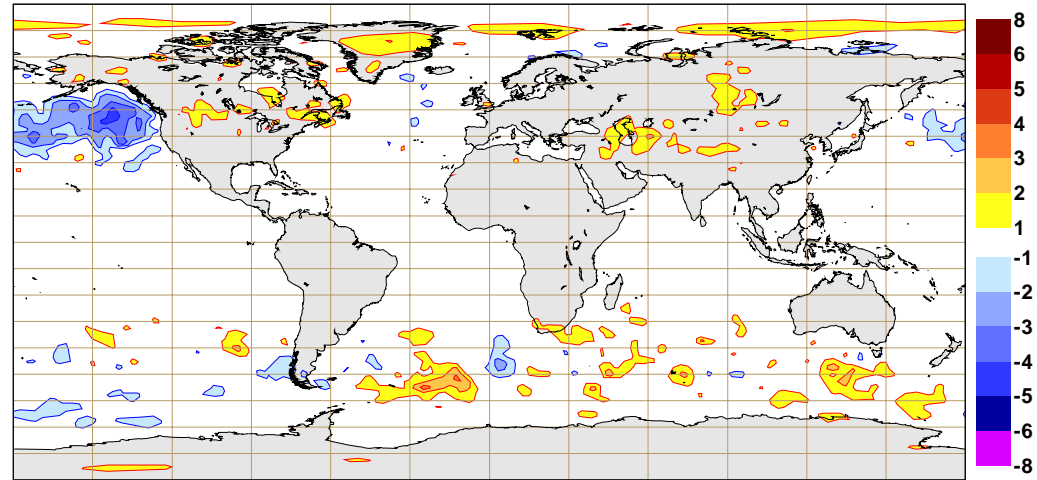
2001-2003

(c) Z500 Difference D+3 FC-Analysis (DJFM 2001-2003)

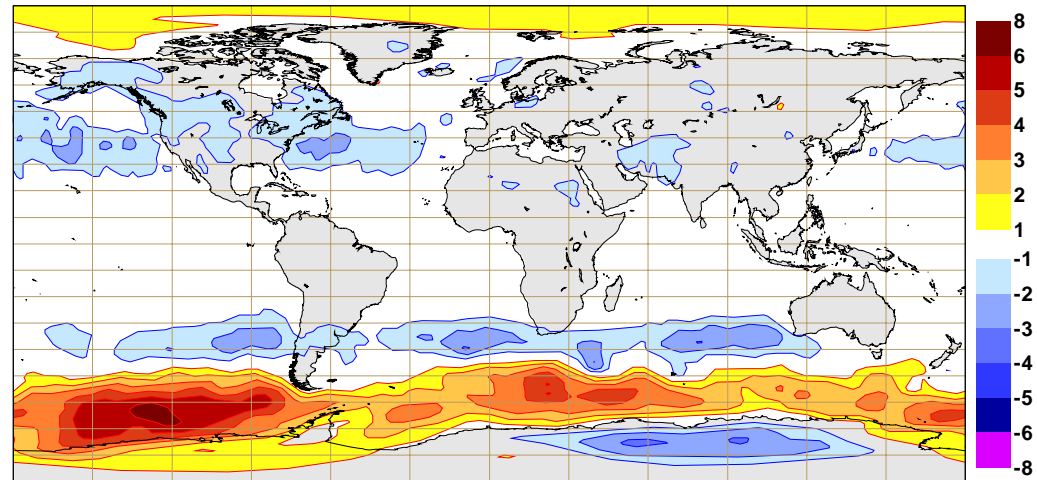


Synoptic Z500 Activity in Different Analyses

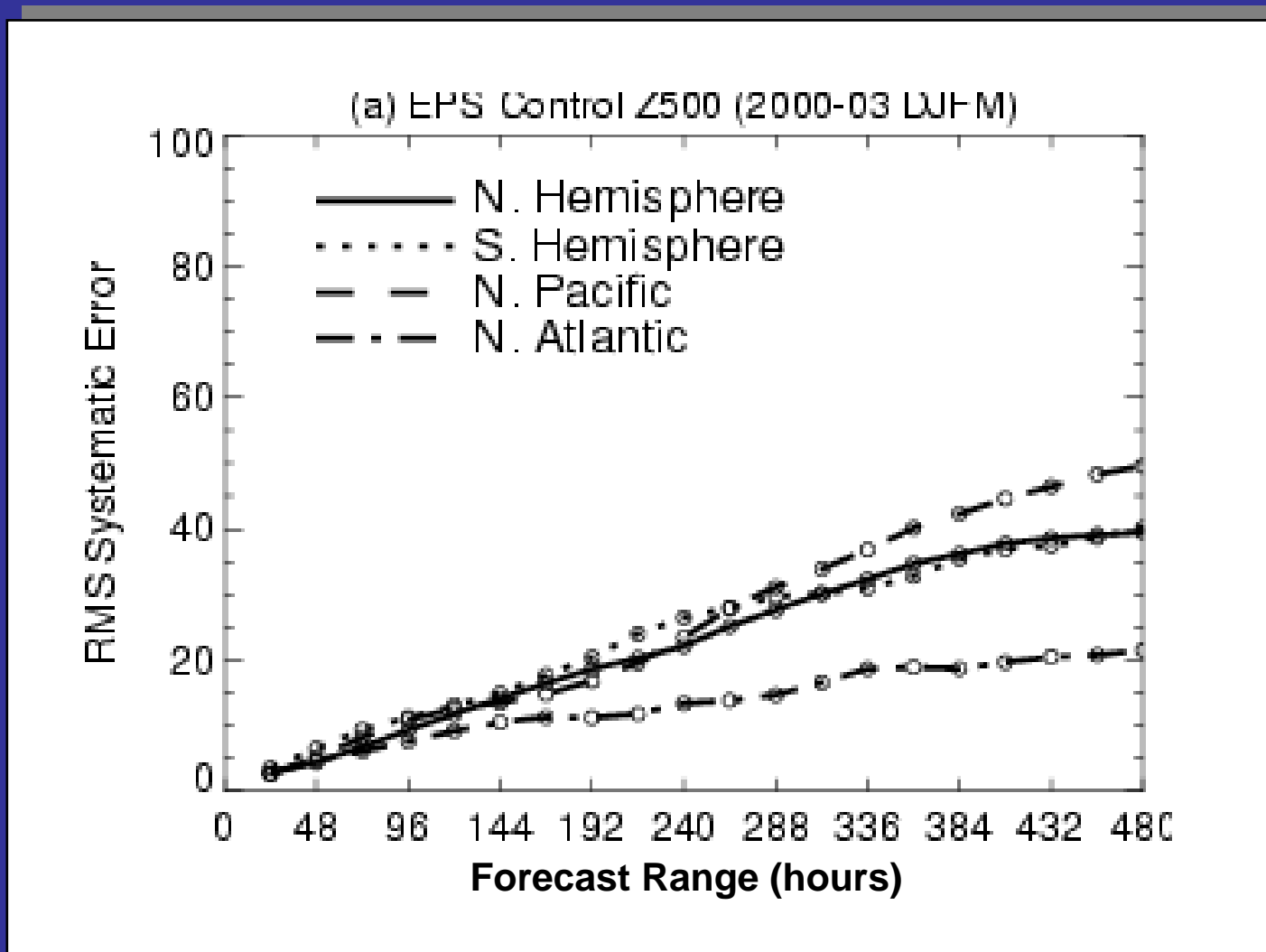
Difference Synoptic Z500 Activity: OD-ERA40 (DJFM 2000-01)



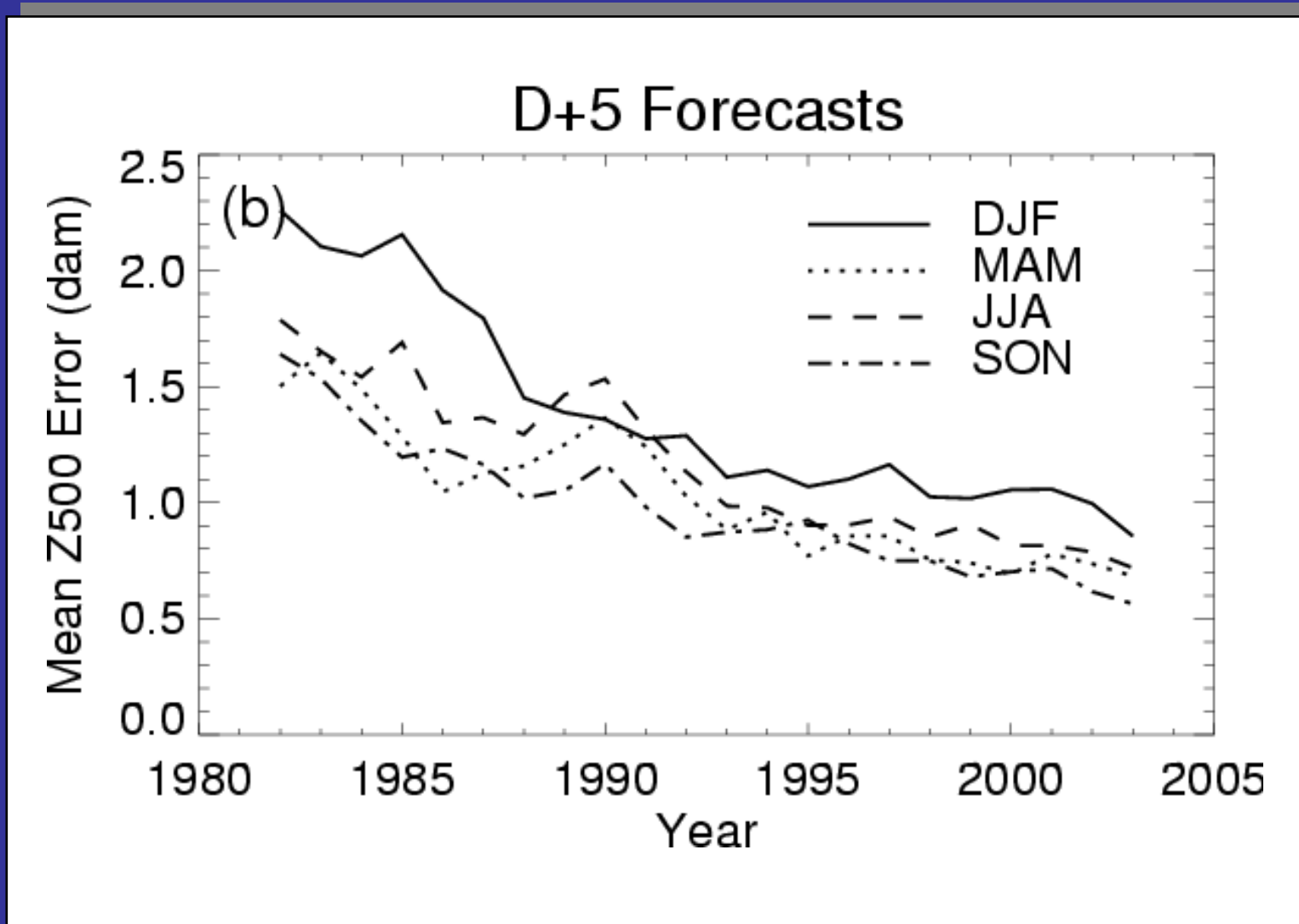
Difference Synoptic Z500 Activity: ERA40-ERA15 (DJFM 1979-92)



Systematic Error Growth: EPSC Z500 (DJFM 2000-03)

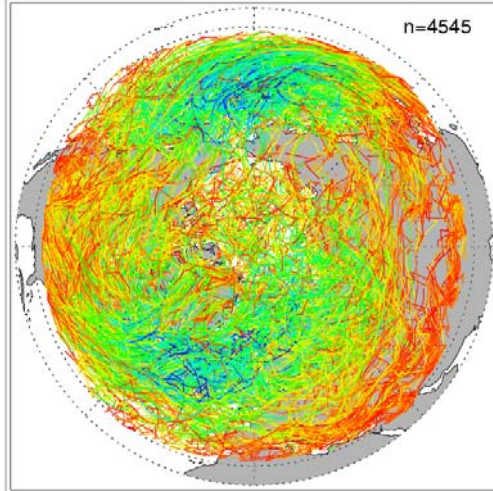


Reduction of Systematic Errors (1981-2003)

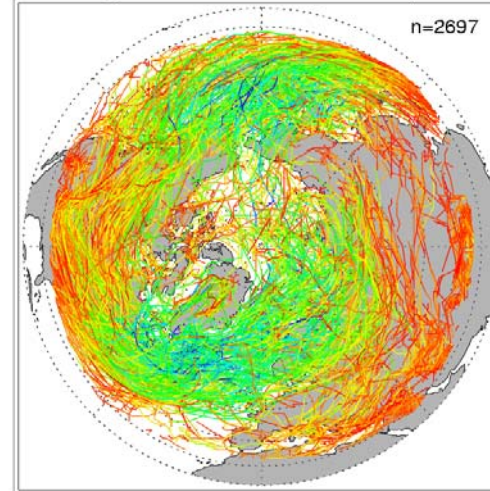


Extratropical Cyclone Tracks (1995-2001)

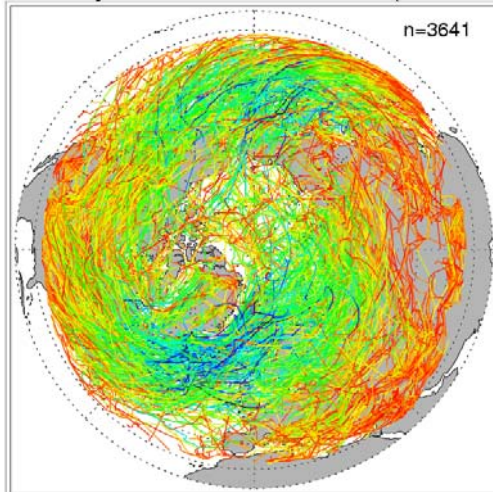
ERA-40 Cyclones DJFM 1995-2000 (T159L60)



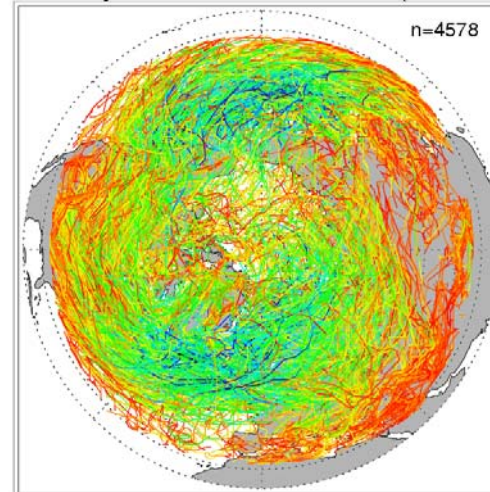
Model Cyclones DJFM 1995-2000 (T95L60)



Model Cyclones DJFM 1995-2000 (T159L60)



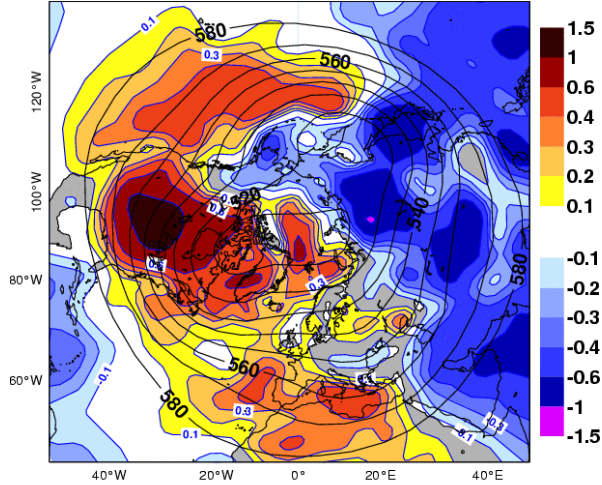
Model Cyclones DJFM 1995-2000 (T255L40)



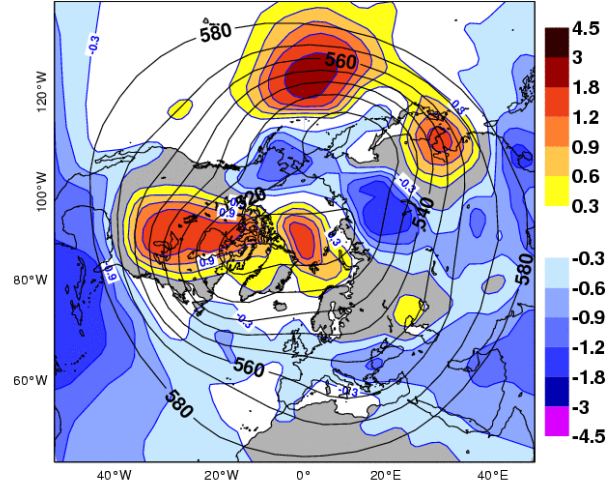
Systematic Z500 Error Growth: Medium-Range (DJFM 1960-2001)

D+1

(a) Z500 Difference D+1 FC-ERA40 (DJFM 1960-2001)



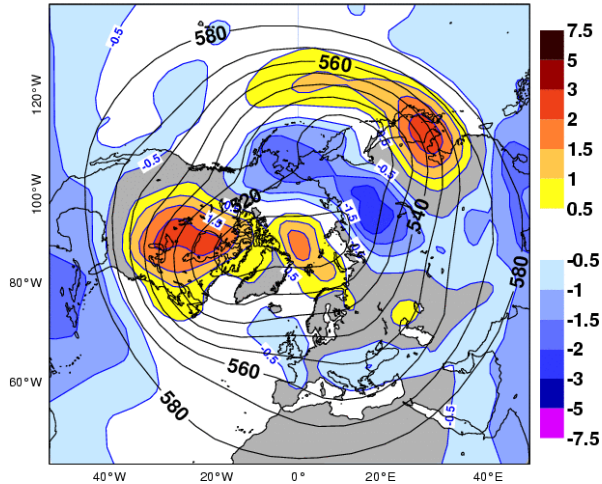
(b) Z500 Difference D+3 FC-ERA40 (DJFM 1960-2001)



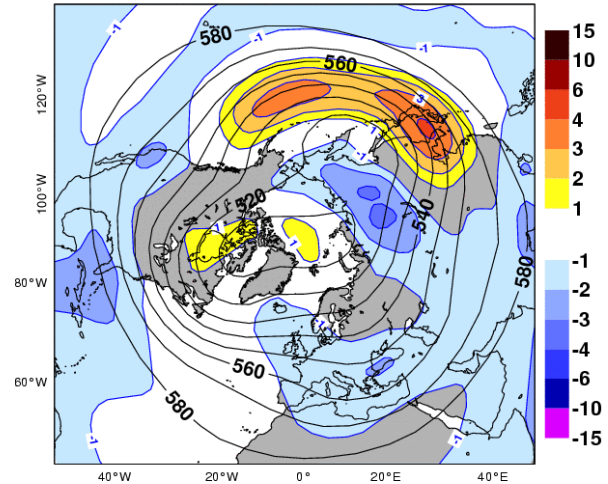
D+3

D+5

(c) Z500 Difference D+5 FC-ERA40 (DJFM 1960-2001)



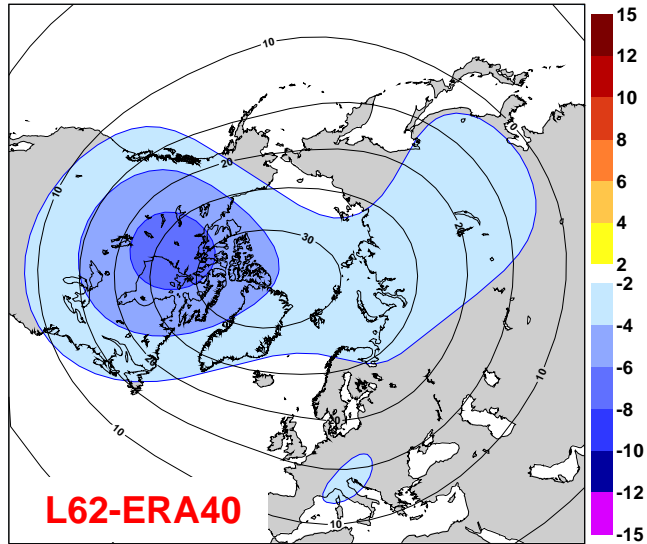
(d) Z500 Difference D+10 FC-ERA40 (DJFM 1960-2001)



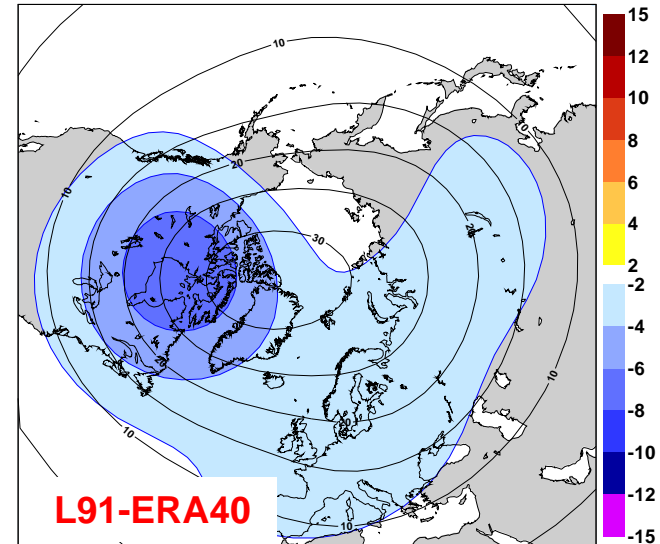
D+10

Planetary-Scale Z50 Variability (k=1-5)

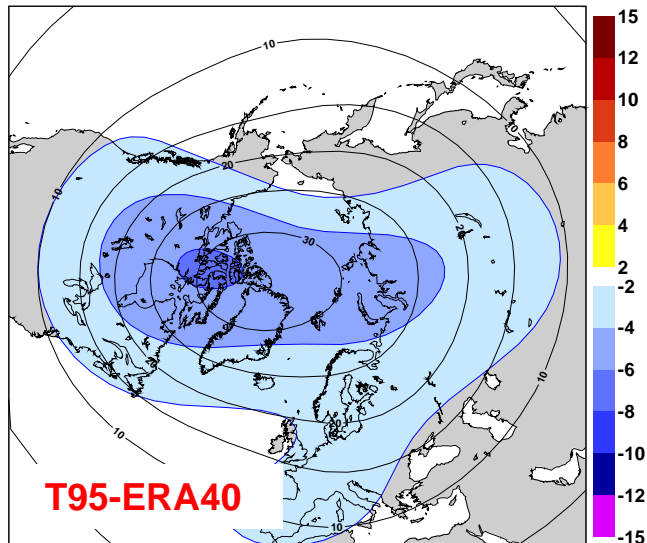
Standard Deviation: Planetary-Scale Z50 Variability
(k=1-5 er40 and eqzy-er40 12-3 1962-2001)



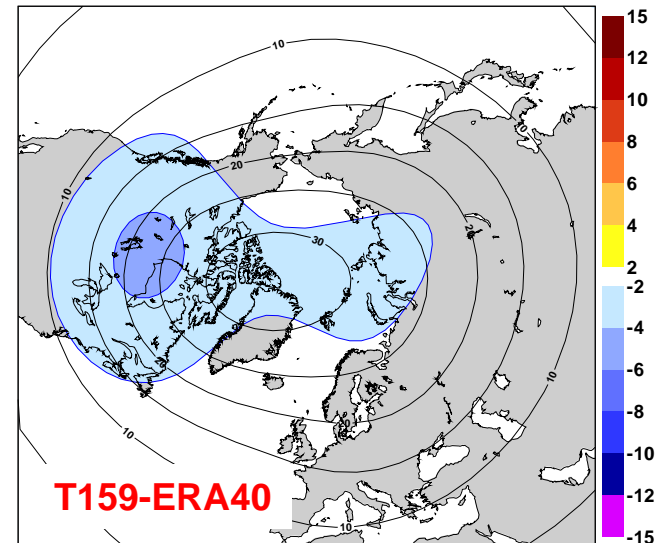
Standard Deviation: Planetary-Scale Z50 Variability
(k=1-5 er40 and eqz8-er40 12-3 1962-2001)



Standard Deviation: Planetary-Scale Z50 Variability
(k=1-5 er40 and elpi-er40 12-3 1962-2001)

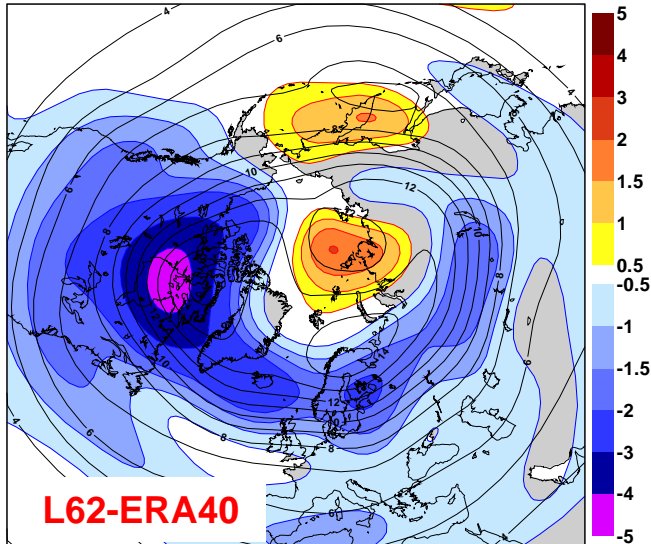


Standard Deviation: Planetary-Scale Z50 Variability
(k=1-5 er40 and em3i-er40 12-3 1962-2001)

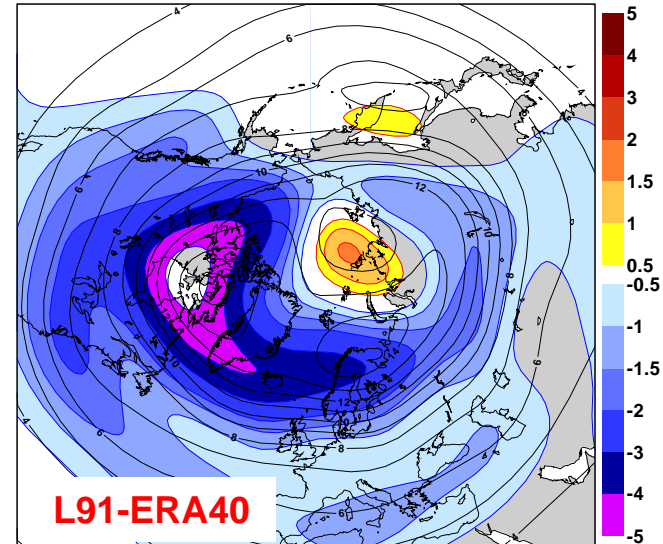


Synoptic-Scale Z50 Variability

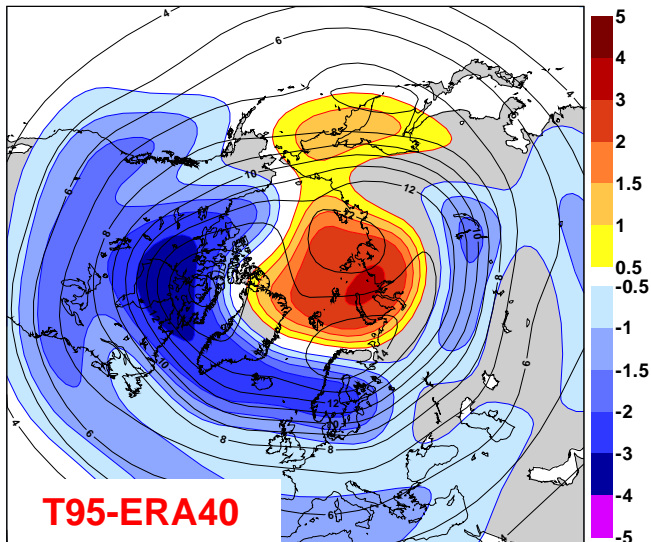
Standard Deviation: Synoptic-Scale Z50 Variability
(k=6-12 er40 and eqzy-er40 12-3 1962-2001)



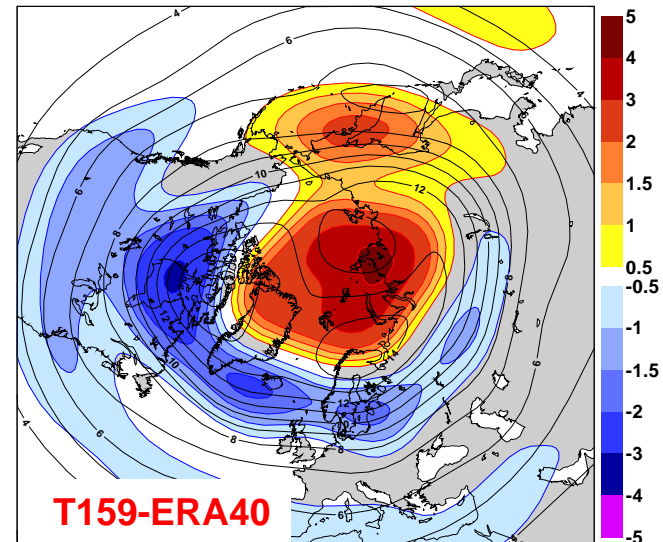
Standard Deviation: Synoptic-Scale Z50 Variability
(k=6-12 er40 and eqz8-er40 12-3 1962-2001)



Standard Deviation: Synoptic-Scale Z50 Variability
(k=6-12 er40 and elpi-er40 12-3 1962-2001)

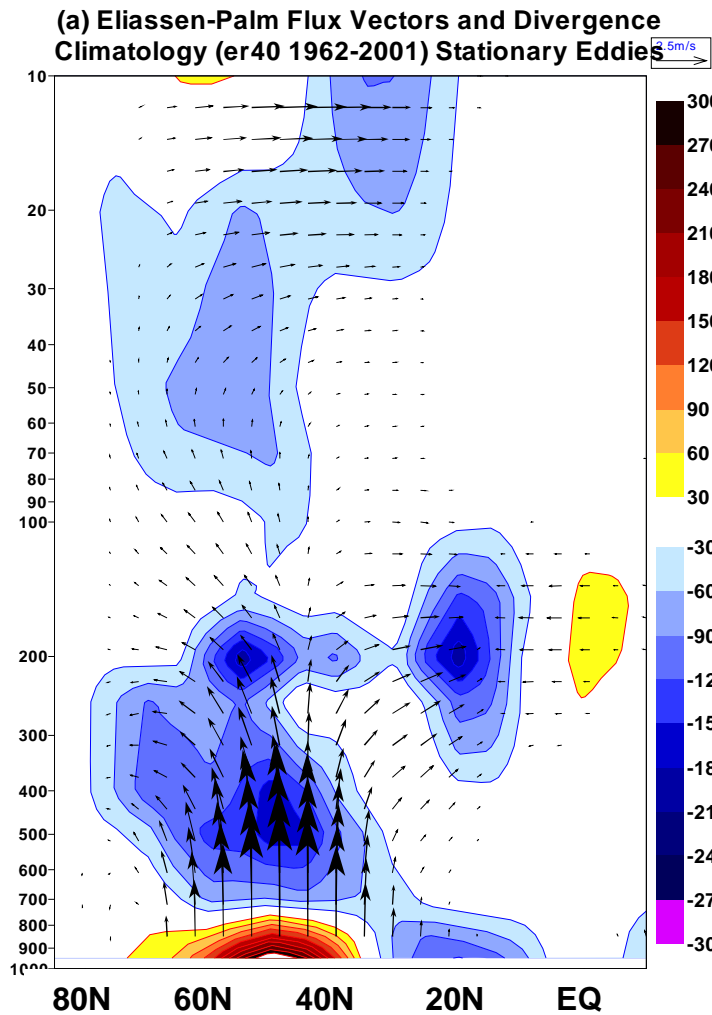


Standard Deviation: Synoptic-Scale Z50 Variability
(k=6-12 er40 and em3i-er40 12-3 1962-2001)

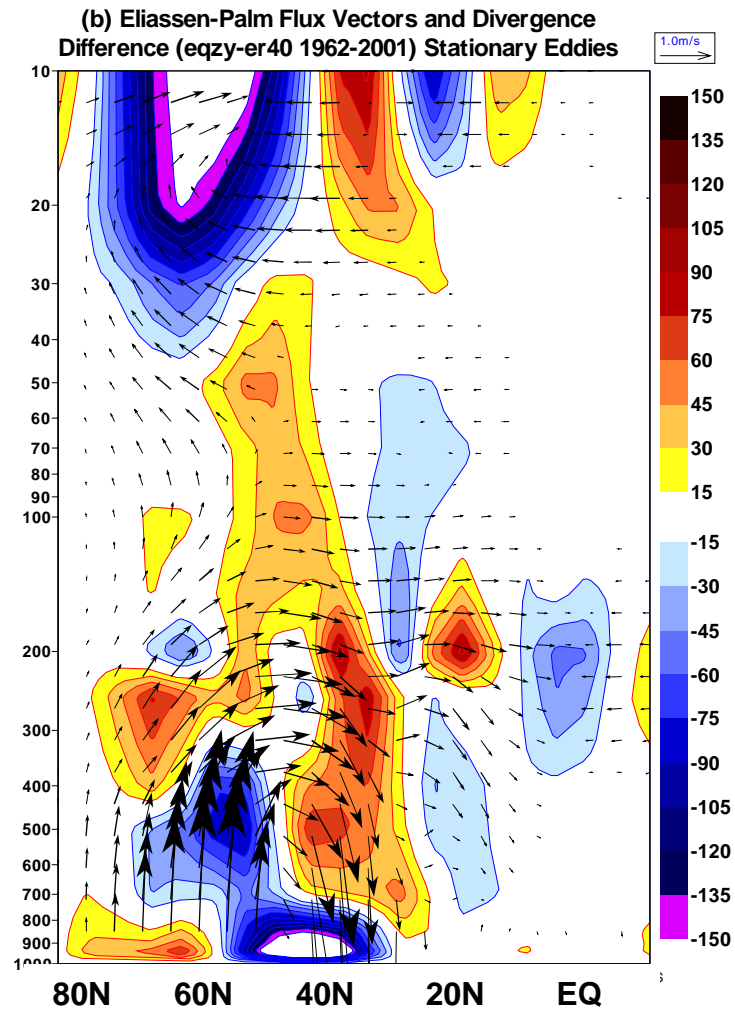


EP-Flux Vectors and Divergence: Stationary Eddies

ERA-40

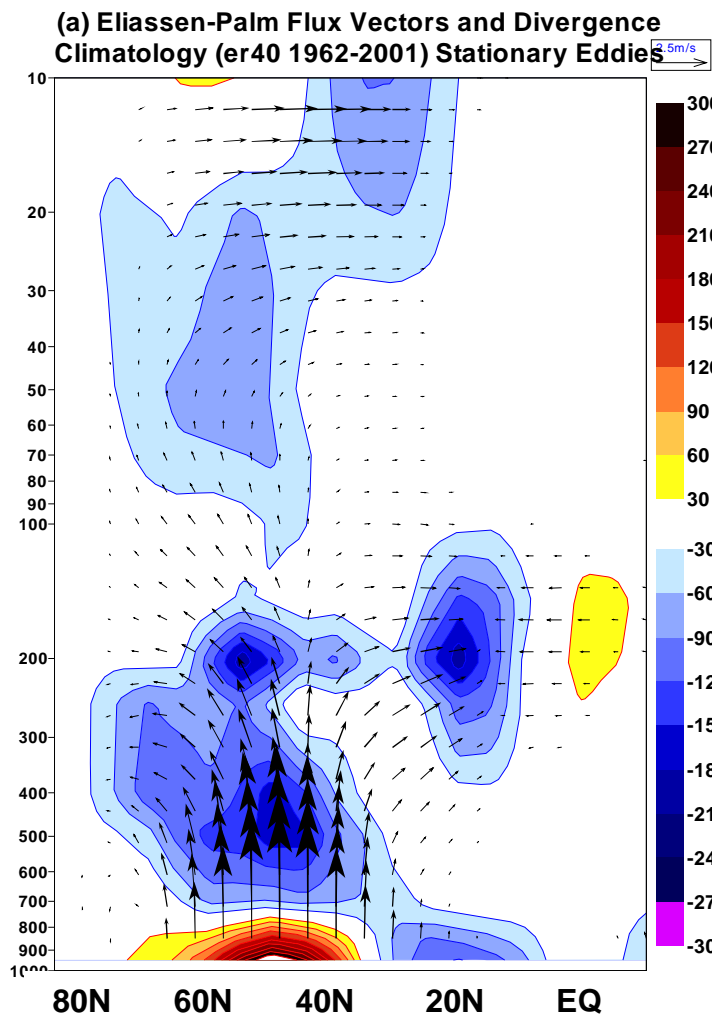


L62-ERA40

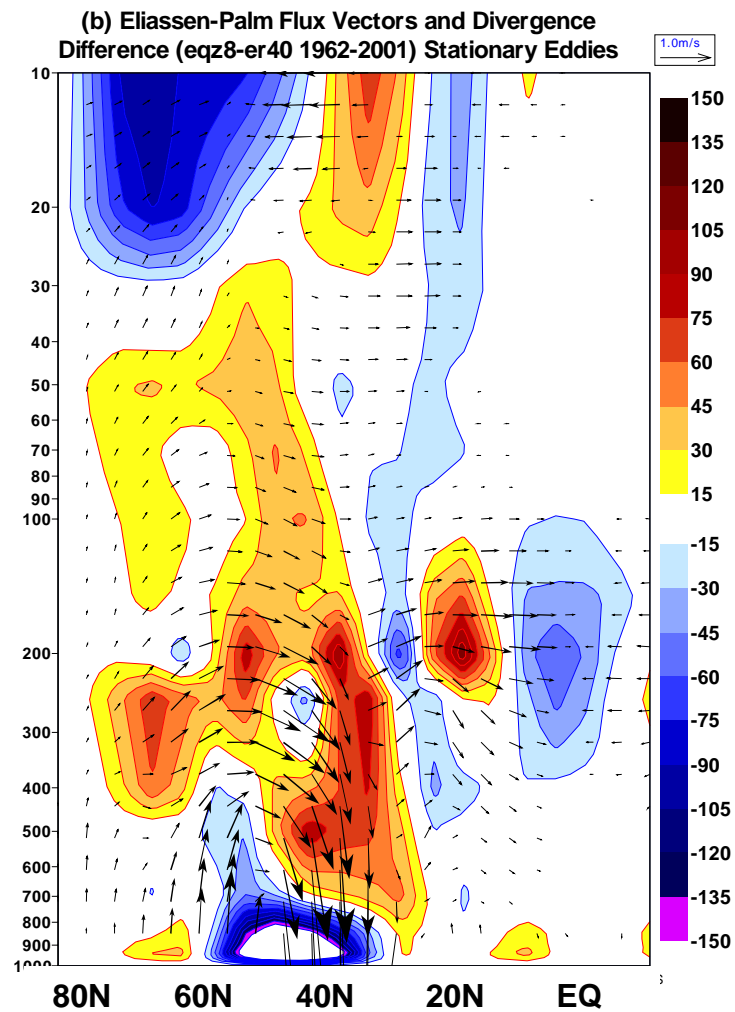


EP-Flux Vectors and Divergence: Stationary Eddies

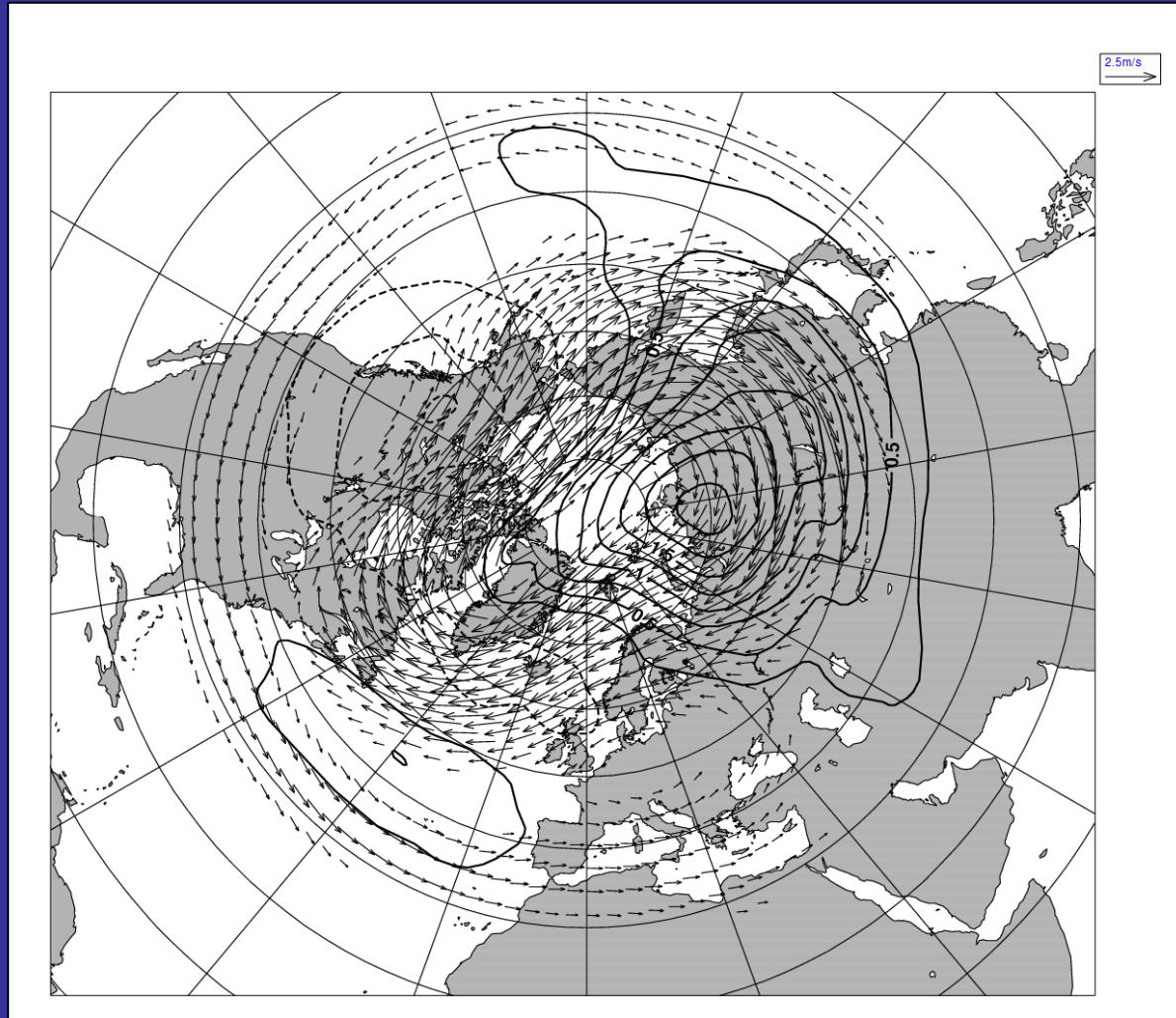
ERA-40



L91-ERA40

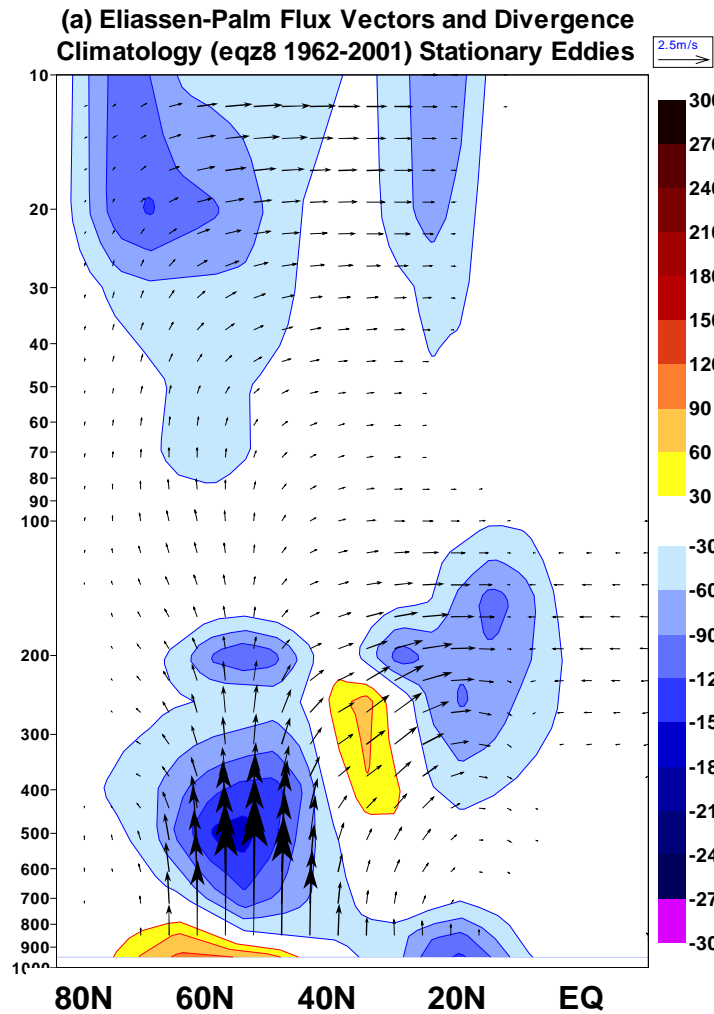


Optimal Stratospheric Forcing (50hPa)

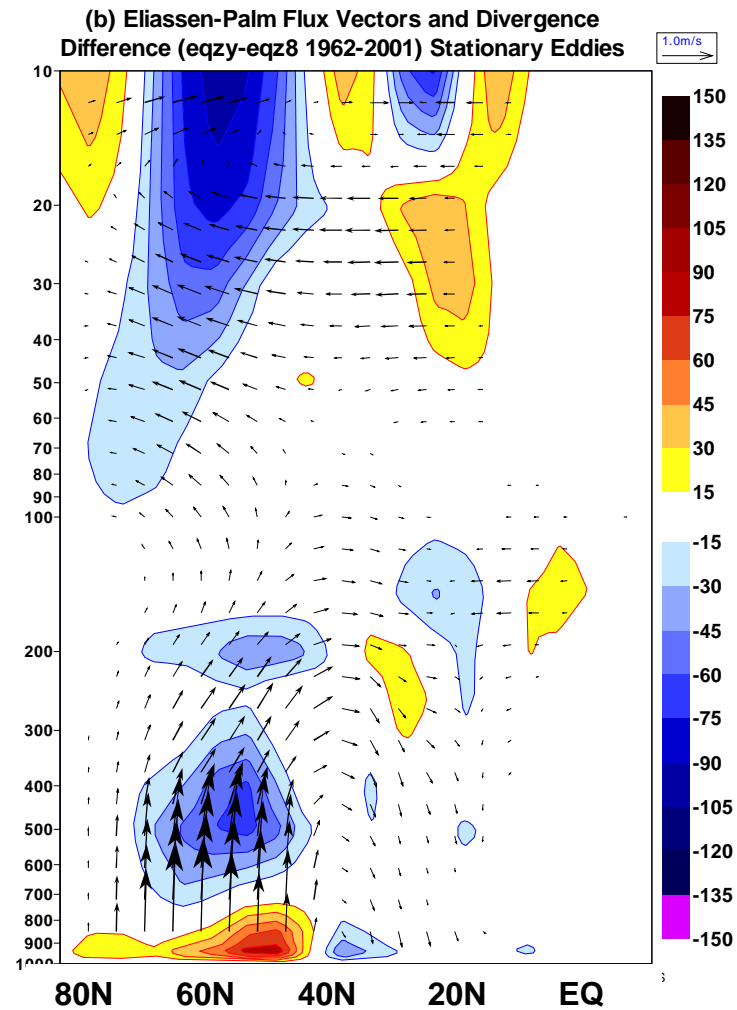


EP-Flux Vectors and Divergence: Stationary Eddies

L91

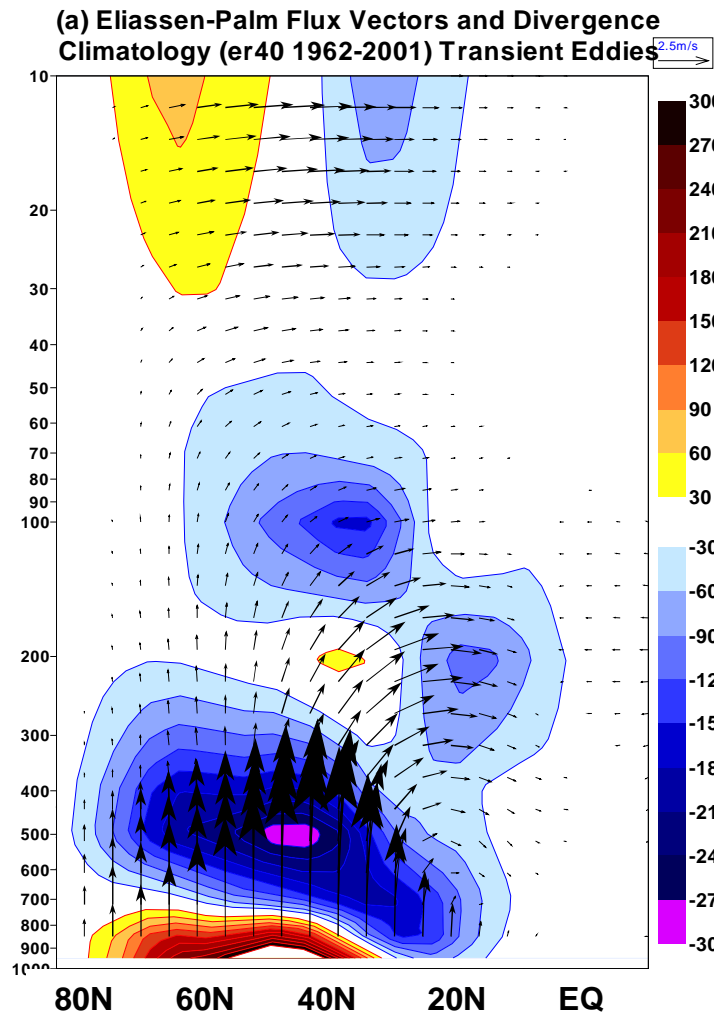


L62-L91

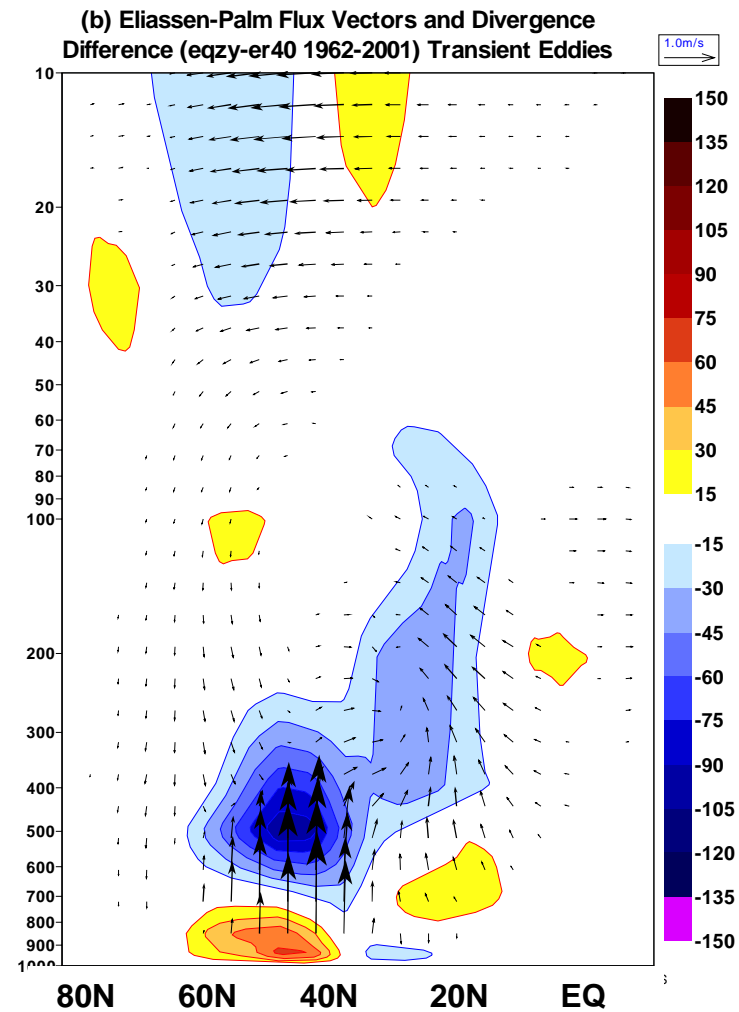


EP-Flux Vectors and Divergence: Transient Eddies

ERA-40

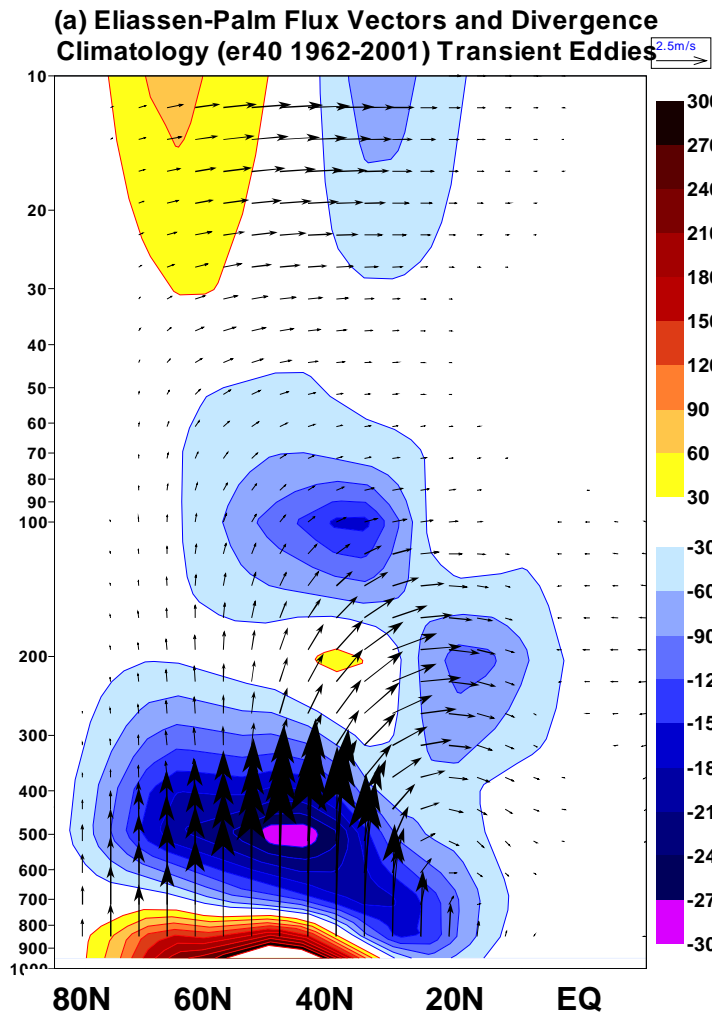


L62-ERA40

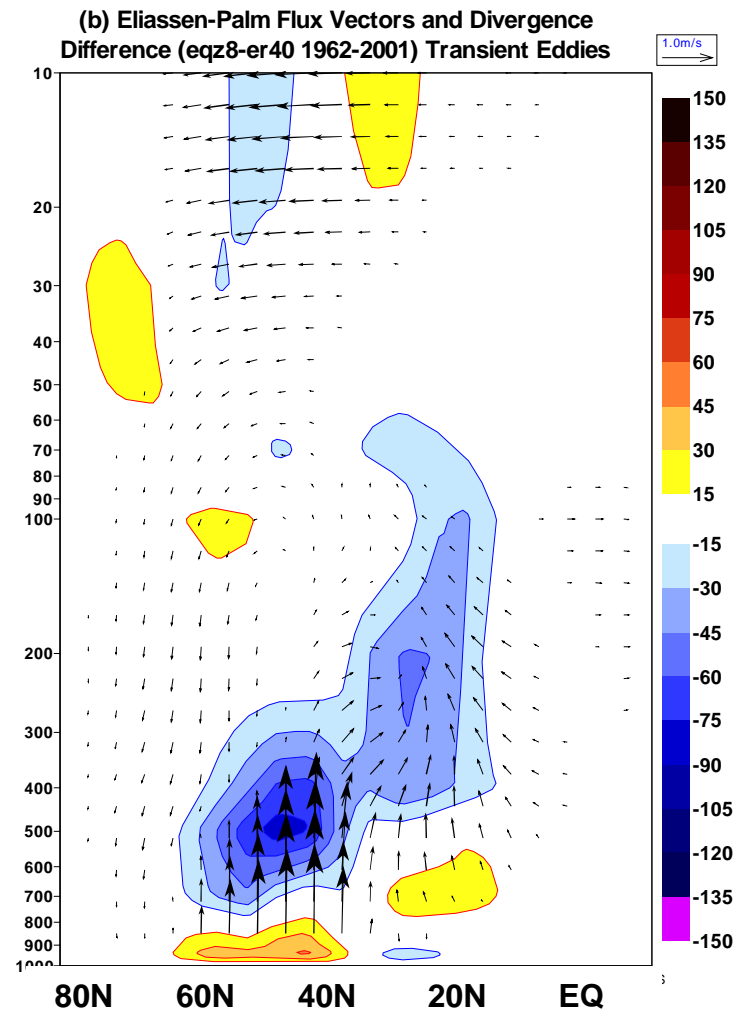


EP-Flux Vectors and Divergence: Transient Eddies

ERA-40

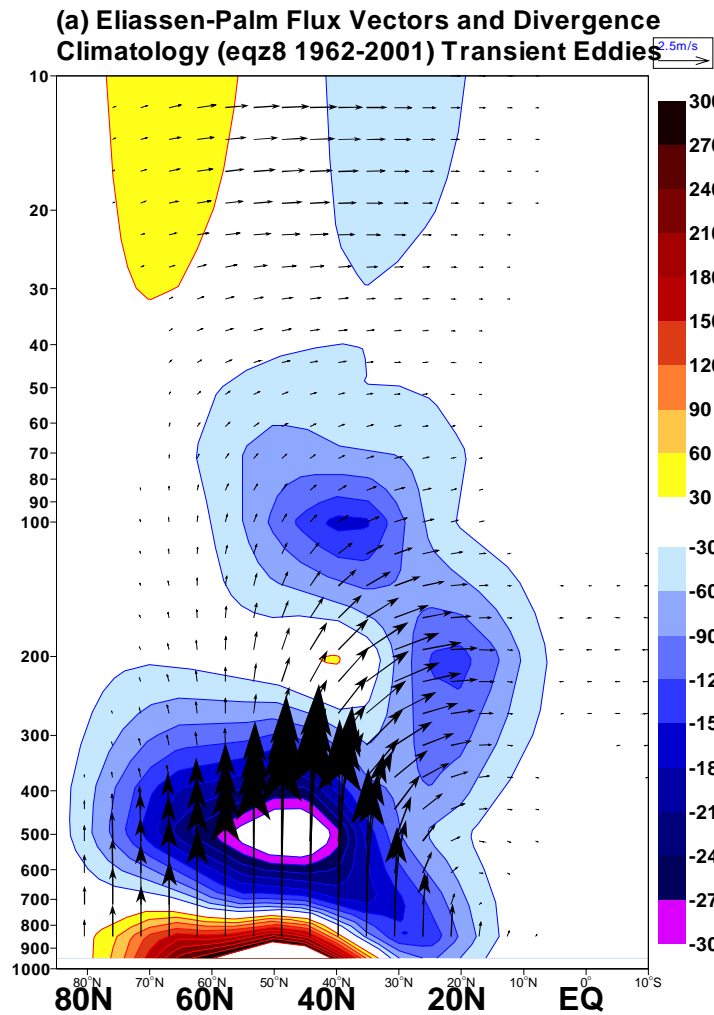


L91-ERA40

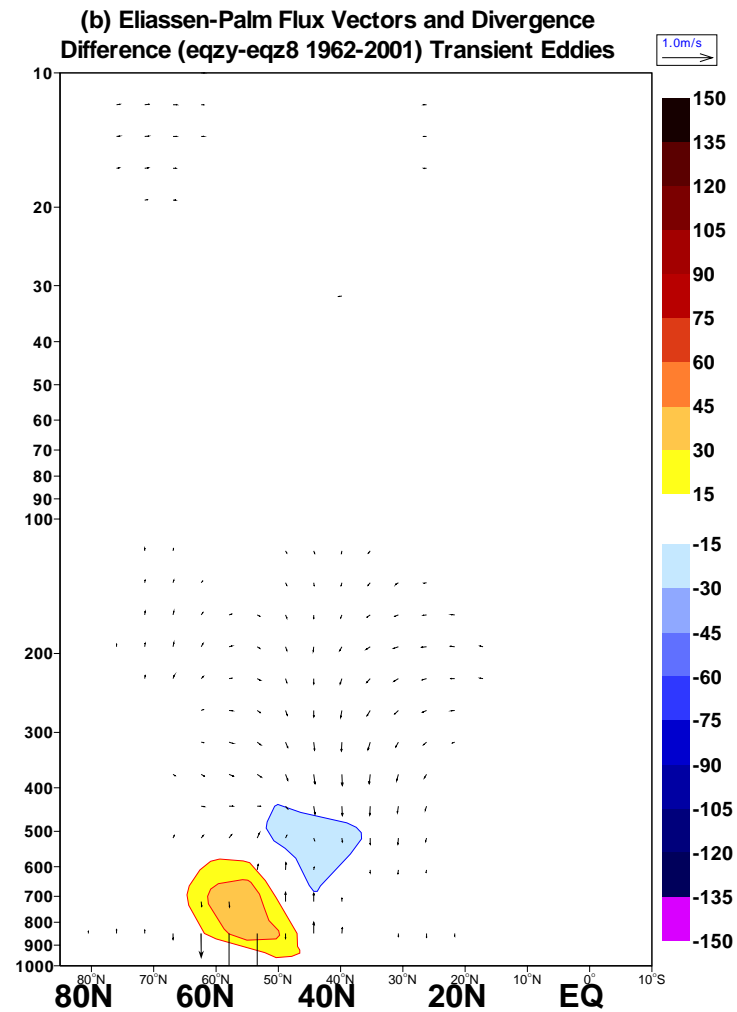


EP-Flux Vectors and Divergence: Transient Eddies

L91

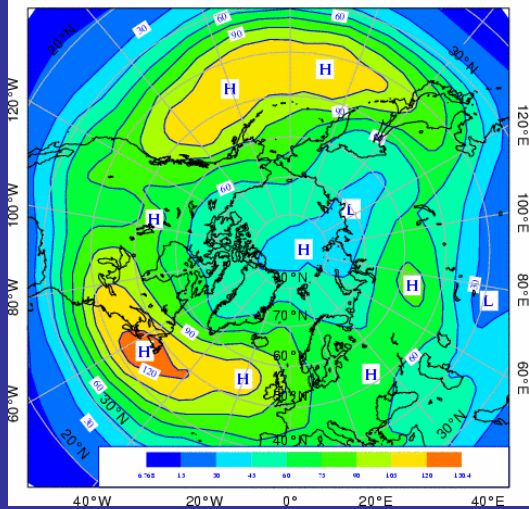


L62-L91

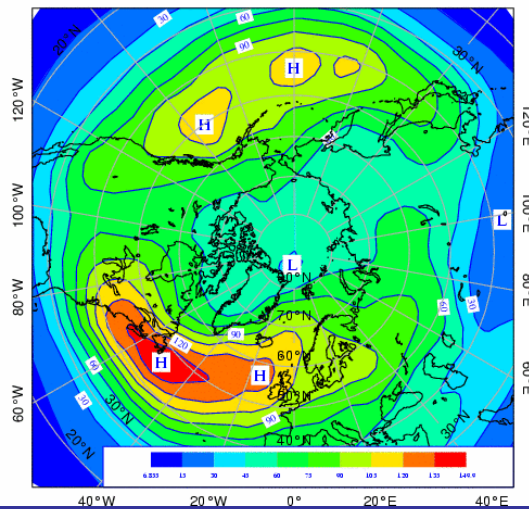


Synoptic Z500 Activity D+21-D+30

Weak Vortex Experiment



Strong Vortex Experiment



Strong - Weak Vortex

