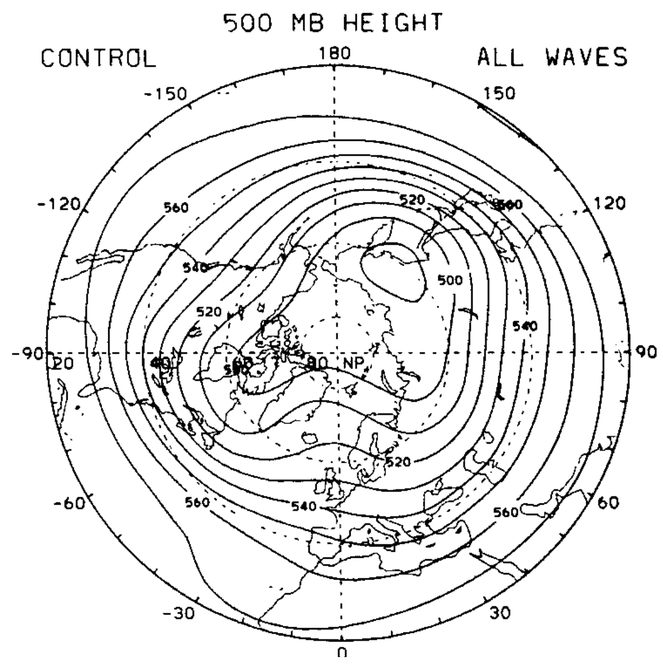
Stratosphere Effects on the Northern Hemisphere Weather and Climate Systems: Sudden Stratospheric Warming (SSW) & Quasi-Biennial Oscillation (QBO)

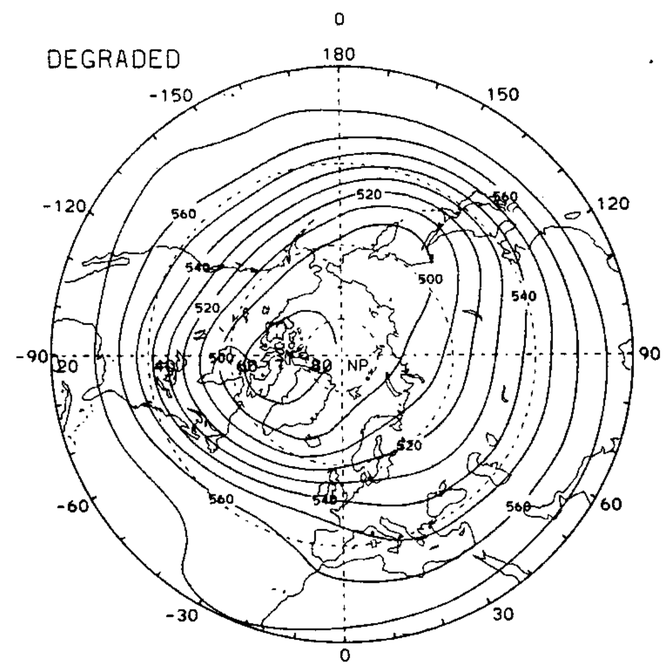
Seok-Woo Son (McGill University)
&
P. Martineau, H.-S. Kim and H. Lin

Importance of Stratosphere in Climate Modelling

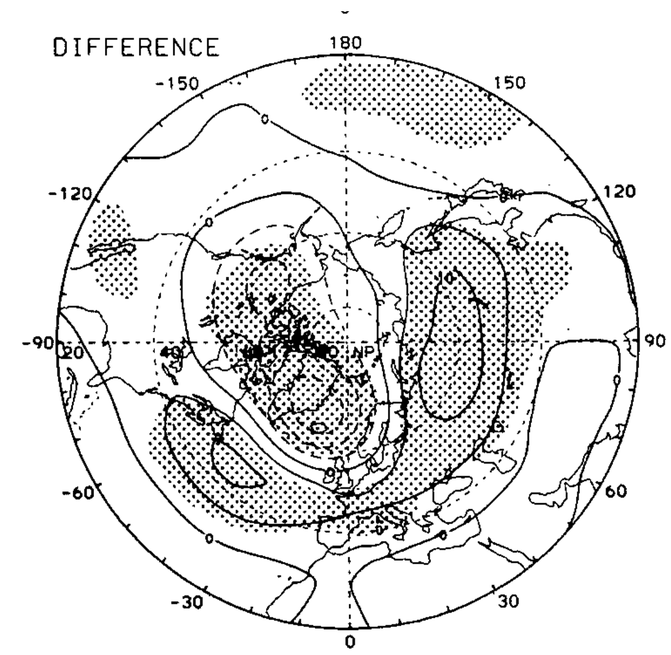
Control Run (500-hPa Z)



Weak Diffusion in Stratosphere



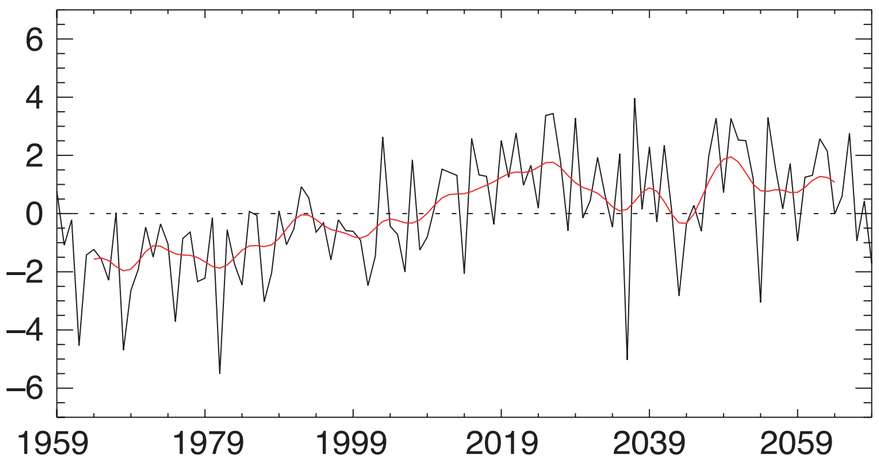
Difference



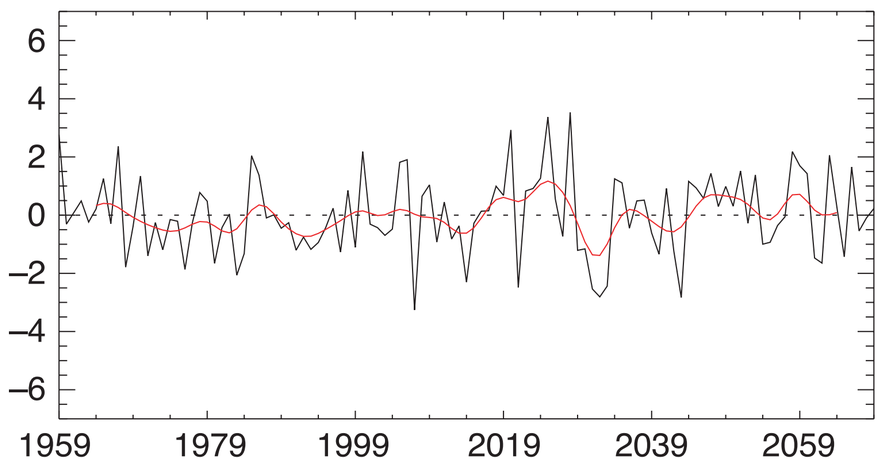
Stratosphere influences tropospheric circulations significantly
(Boville, 1984).

Importance of Stratosphere in Climate Modelling

L23 - model top 0.002hPa (NAM index)



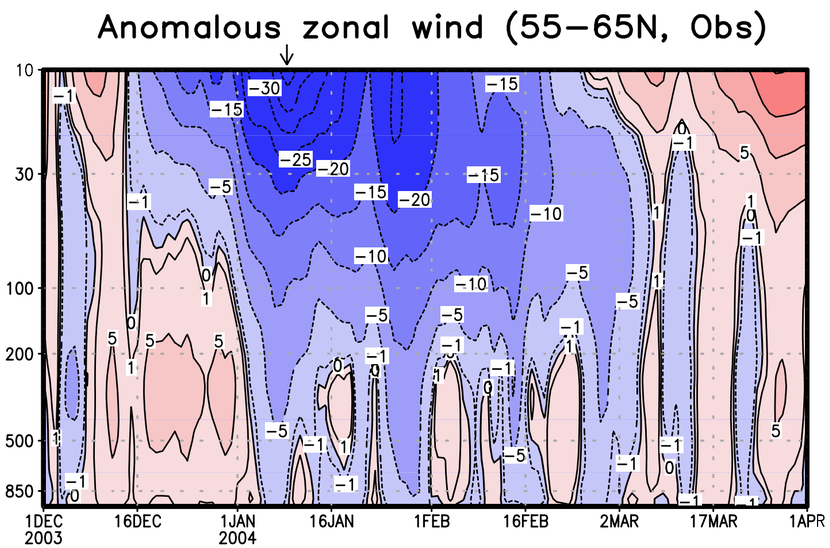
L9 - model top 10hPa (NAM index)



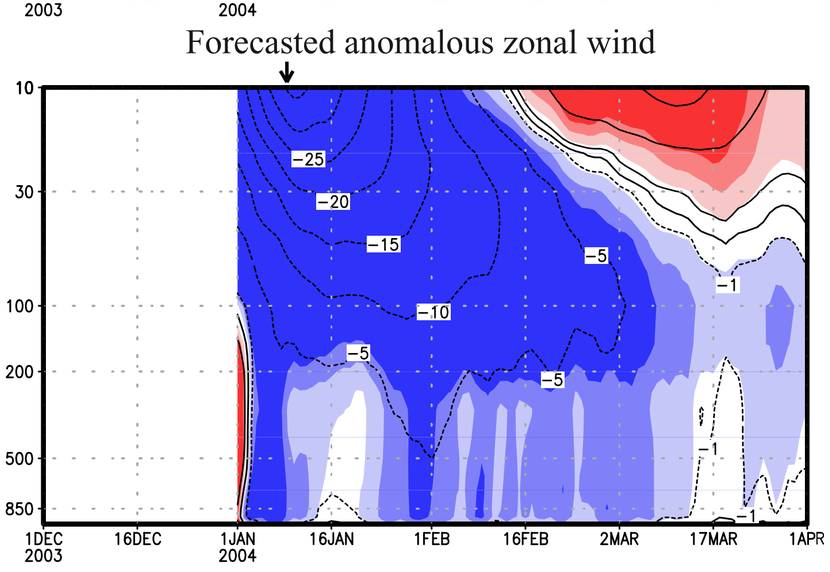
The NAM-index trend is captured only in climate models that include a realistic representation of the stratosphere

(Shindell et al., 1999).

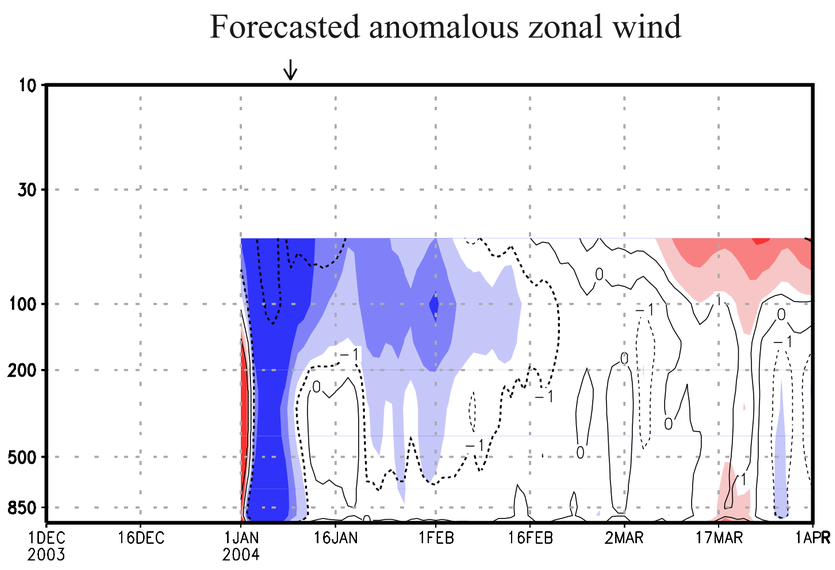
Importance of Stratosphere in Extended Forecast



Stratospheric processes are important for a medium-range weather forecast (Kuroda 2008).



L40 top at 0.4 hPa



L29 top at 40 hPa

Dominant Variability in the Stratosphere

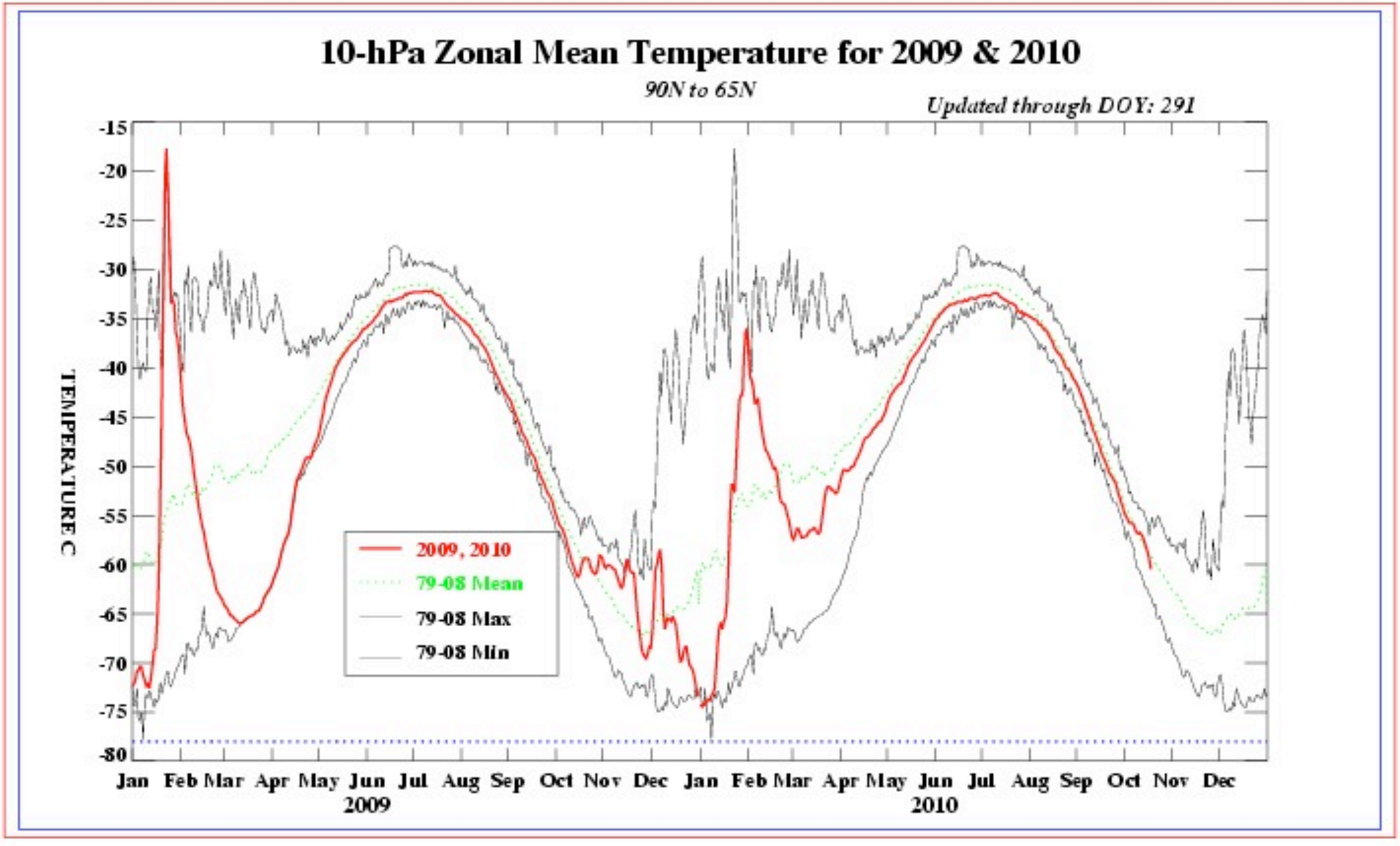
Intra-seasonal time scale: Sudden Stratospheric Warming (SSW)

Inter-annual variability: Quasi-Biennial Oscillation (QBO) & Ozone Hole

SSW: Phenomena and Robustness among Data Sets

with P. Martineau

SSW: Polar Cap 10-hPa [T] during 2009-2010

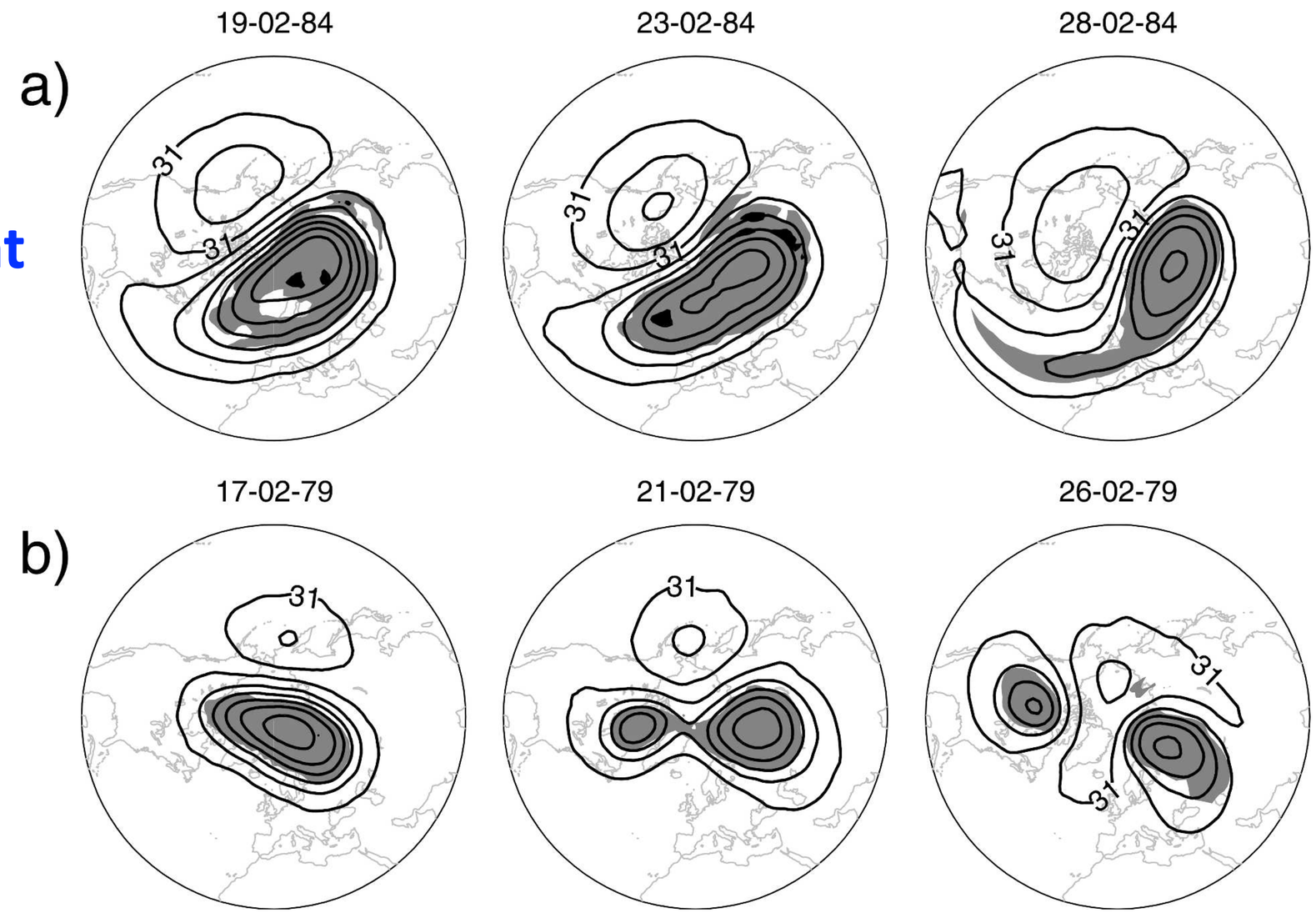


klimatbalans.info

SSW: Two Types of SSW

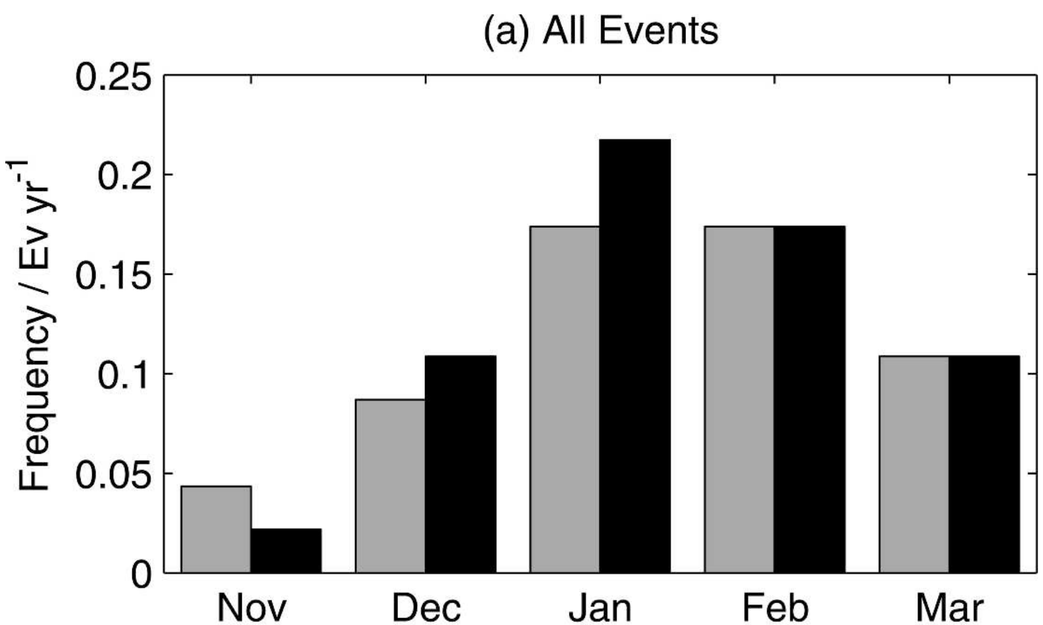
Vortex Displacement

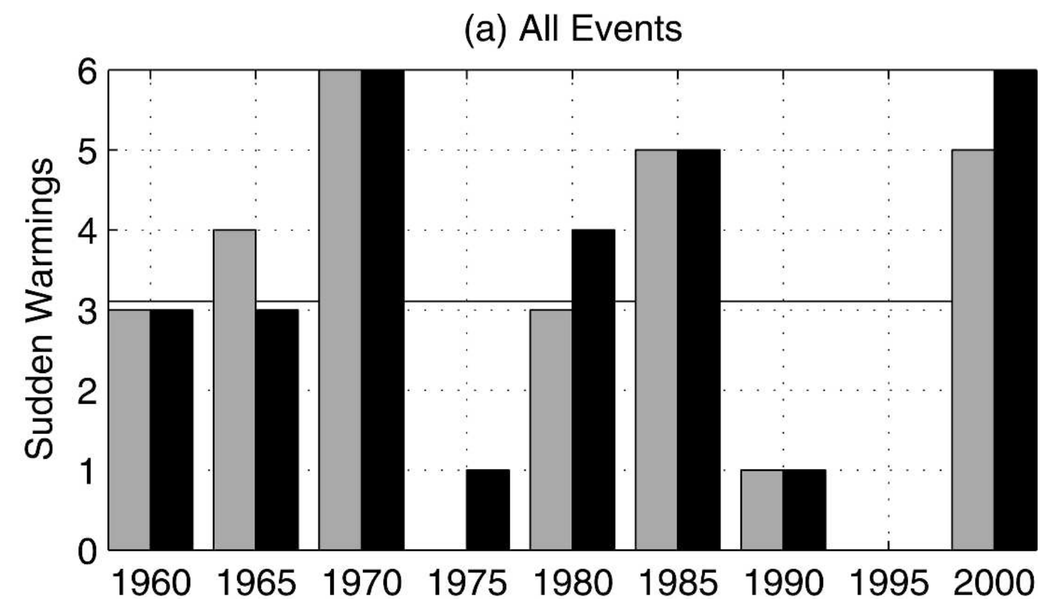
Vortex Split



Charlton and Polvani (2007)

SSW: Frequency of SSW





Grey-NCEP1 & Black-ERA40 from Charlton and Polvani (2007)

SSW occurs once about every other years. It occurs mostly in the NH winter

SSW: Dynamical Mechanisms

Wave-Mean Flow Interaction (e.g., Matsuno 1971)

- Vertically propagating planetary scale waves (wave number 1 or 2) break in the stratosphere, altering the large-scale circulation there
- It is not well understood what generates the planetary scale waves in the troposphere which result in the SSW.

Internal Dynamics (e.g., Scott and Polvani 2006)

- Stratosphere only model often generates the SSW. In this case, the vertical wind shear in the stratosphere plays an important role

SSW: Impacts on the Troposphere

Northern Annular Mode

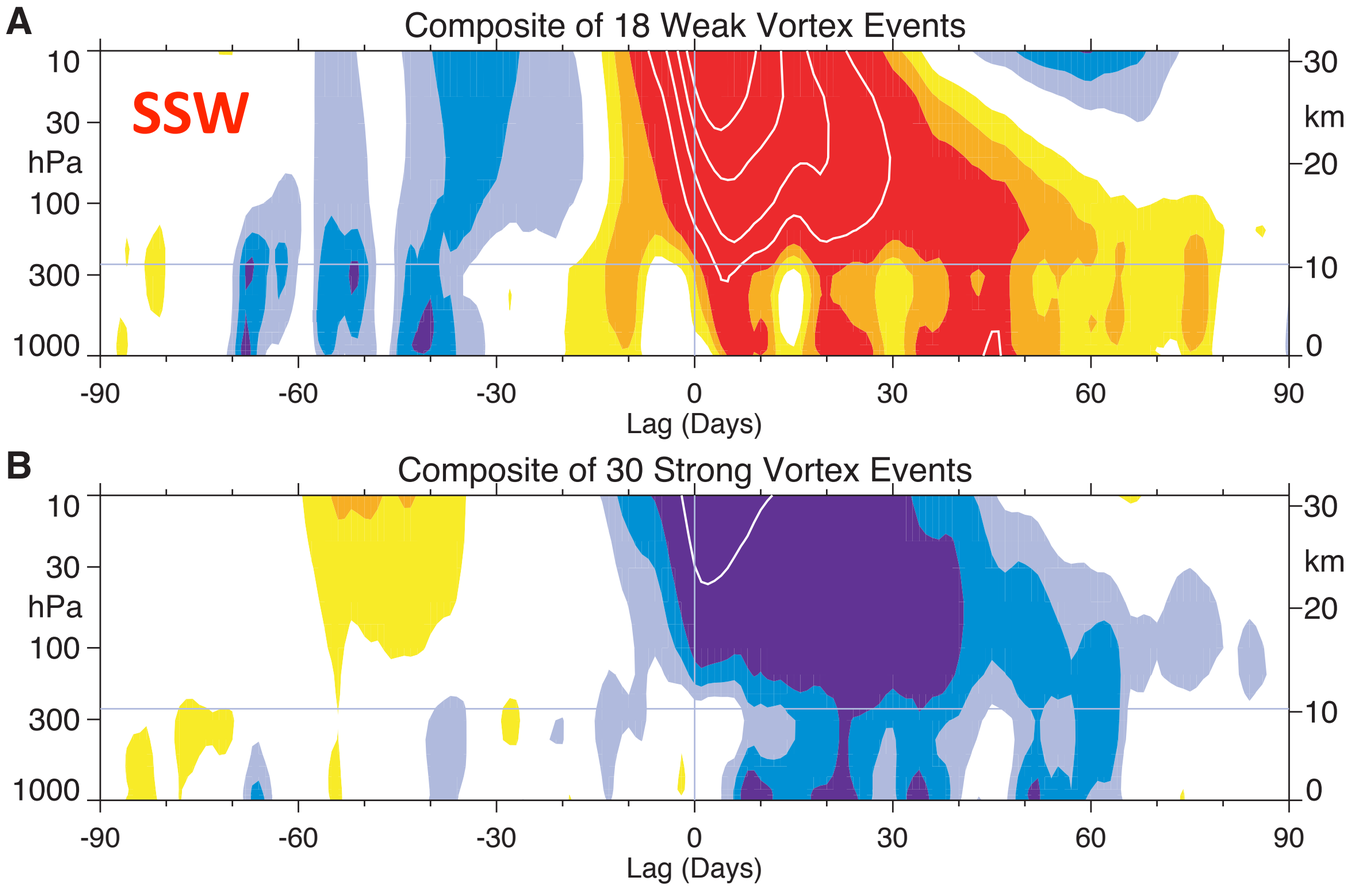


Fig. 2. Composites of time-height development of the northern annular mode for (**A**) 18 weak vortex events and (**B**) 30 strong vortex events. The events are determined by the dates on which the 10-hPa annular mode values cross –3.0 and +1.5, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25, and 0.5 for the white contours. Values between −0.25 and 0.25 are unshaded. The thin horizontal lines indicate the approximate boundary between the troposphere and the stratosphere.

Sea Level Pressure

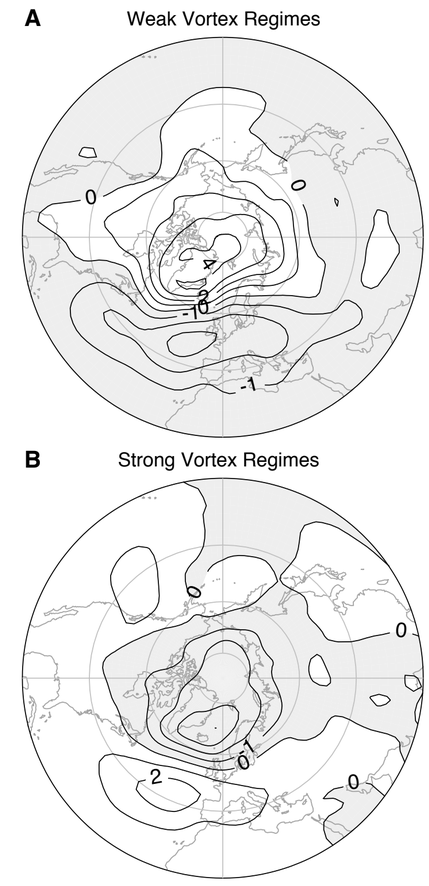


Fig. 3. Average sea-level pressure anomalies (hPa) for (**A**) the 1080 days during weak vortex regimes and (**B**) the 1800 days during strong vortex regimes.

Baldwin and Dunkerton (2001)

Researches at McGill

Researches at McGill

How robust are the SSW and the associated downward propagation in the reanalysis data?

- Inter-comparison between observation (COSMIC GPS RO measurements) and reanalysis data: case study of the 2009 SSW event.
- Inter-comparison among NCEP-NCAR, NCEP-DOE, ERA40 (ERA-Intrim), JRA25 and MERRA in term of polar climate variability.

Under what conditions does downward propagation occur?

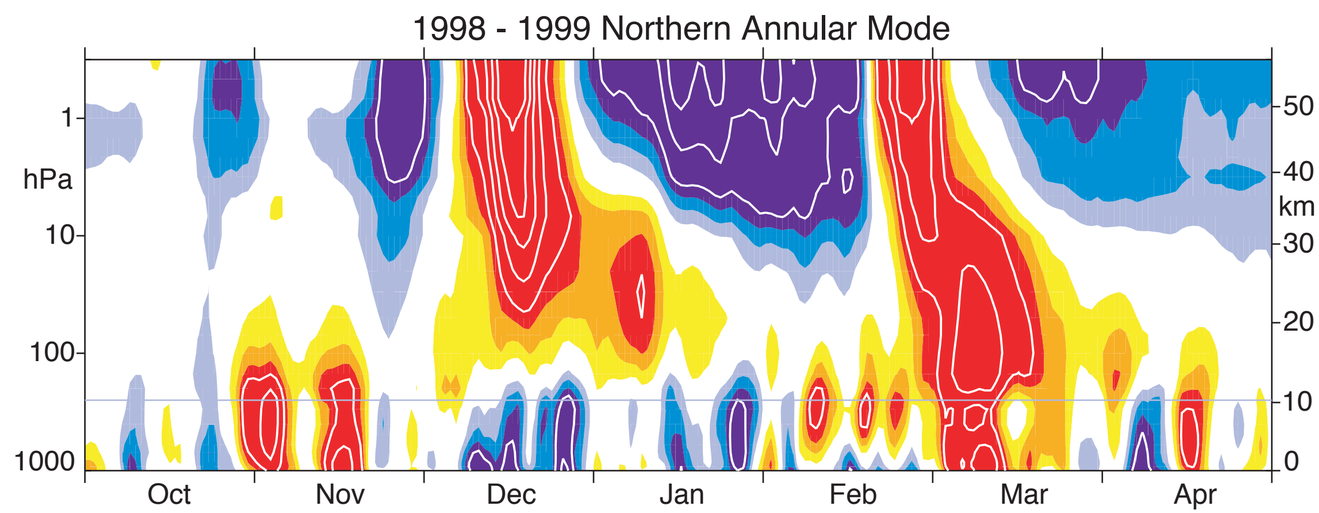
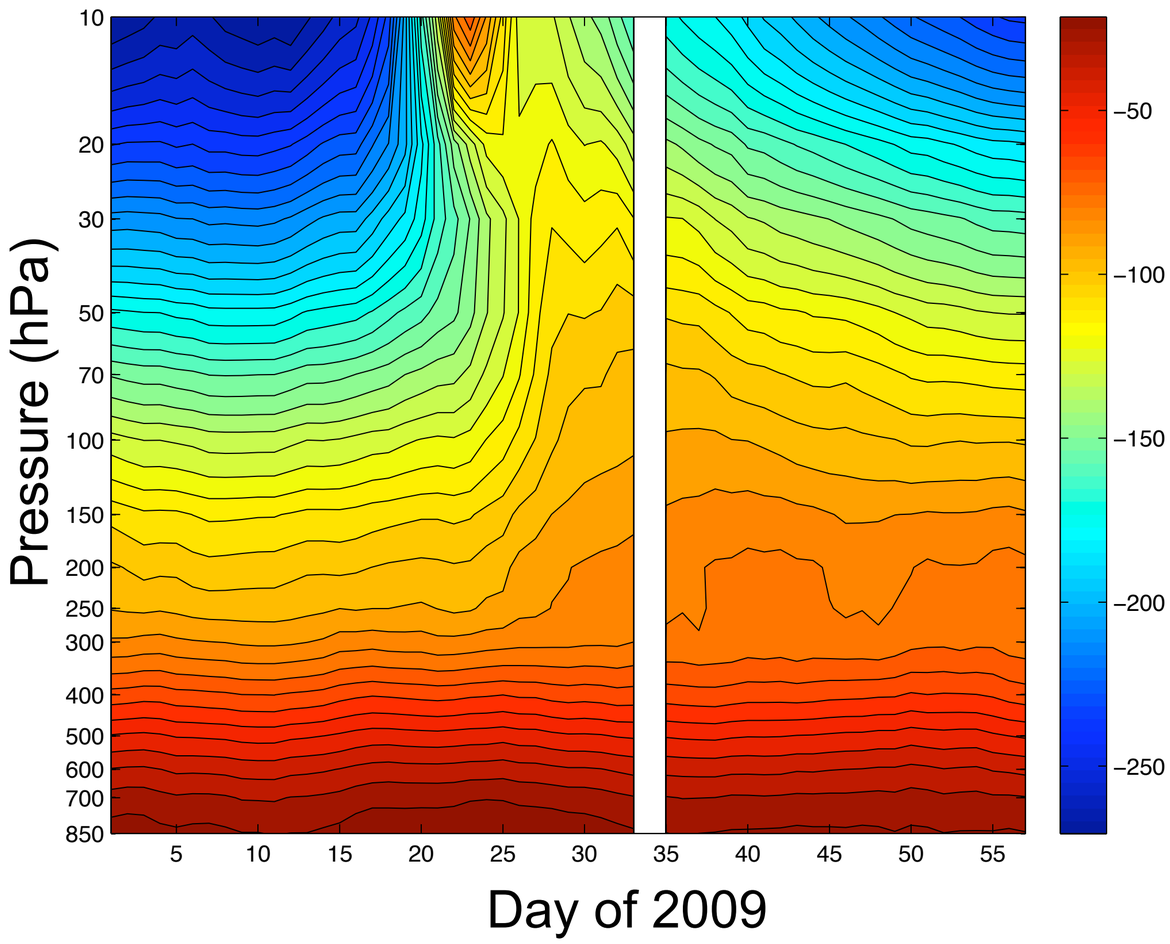


Fig. 1. Time-height development of the northern annular mode during the winter of 1998–1999. The indices have daily resolution and are nondimensional. Blue corresponds to positive values (strong polar vortex), and red corresponds to negative values (weak polar vortex). The contour interval is 0.5, with values between −0.5 and 0.5 unshaded. The thin horizontal line indicates the approximate boundary between the troposphere and the stratosphere.

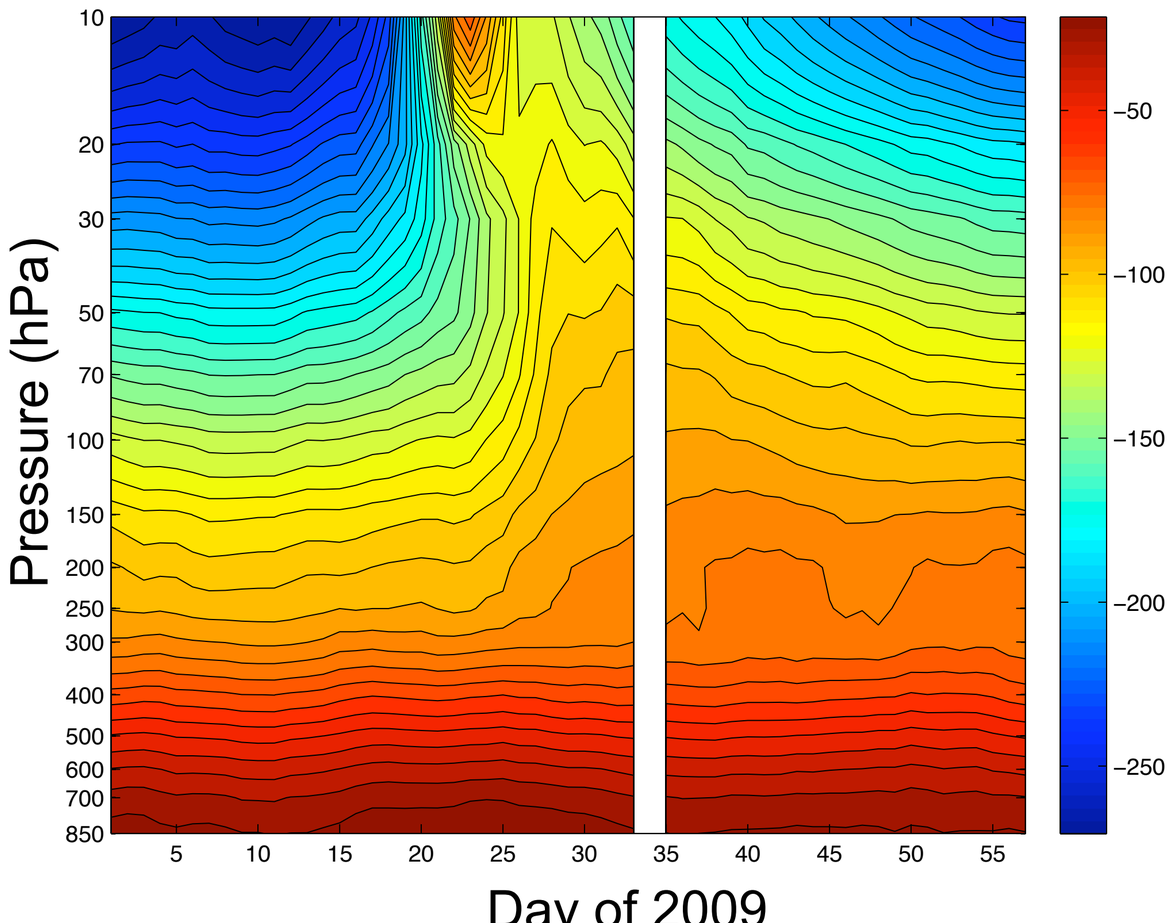
SSW 2009: COSMIC GPS RO Observations

Polar-cap T over 65N-90N

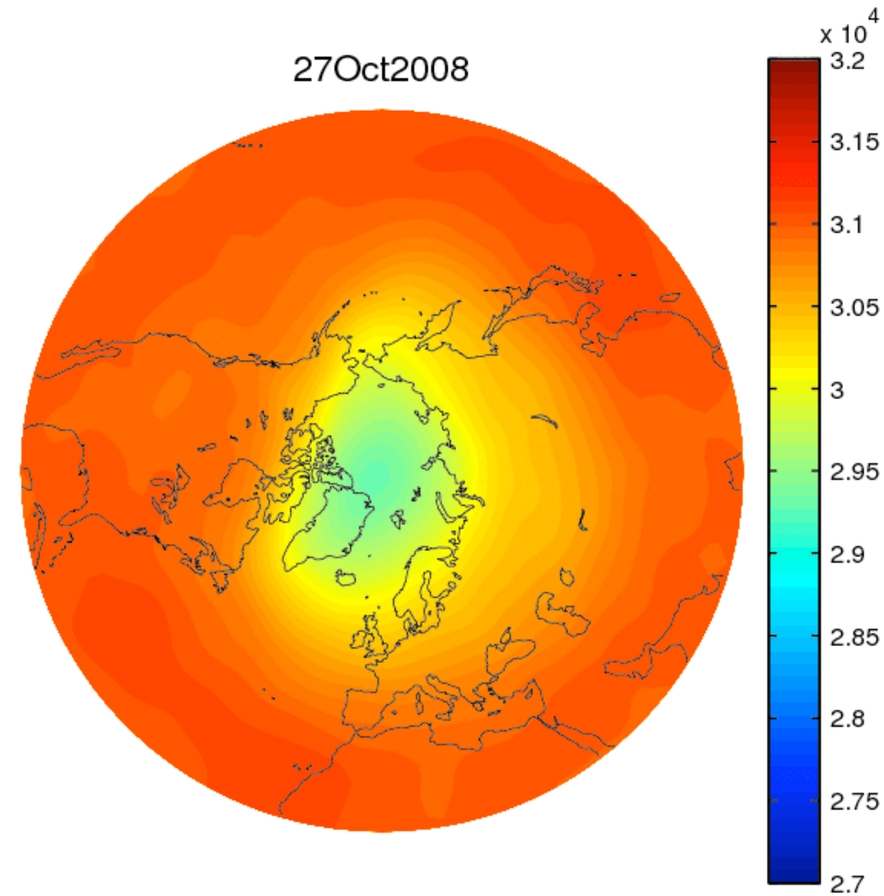


SSW 2009: COSMIC GPS RO Observations

Polar-cap T over 65N-90N

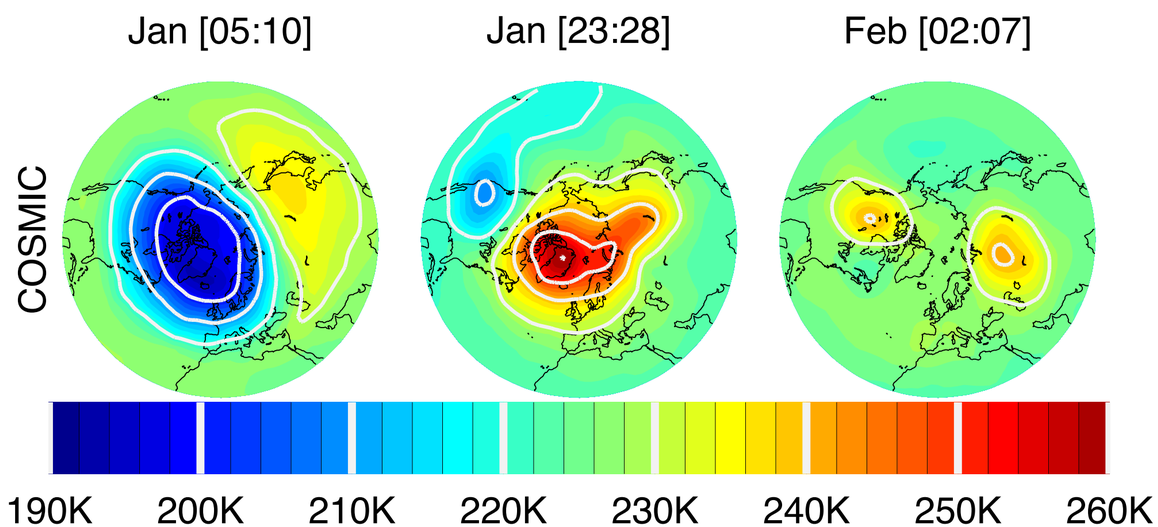


Daily Z at 10 hPa

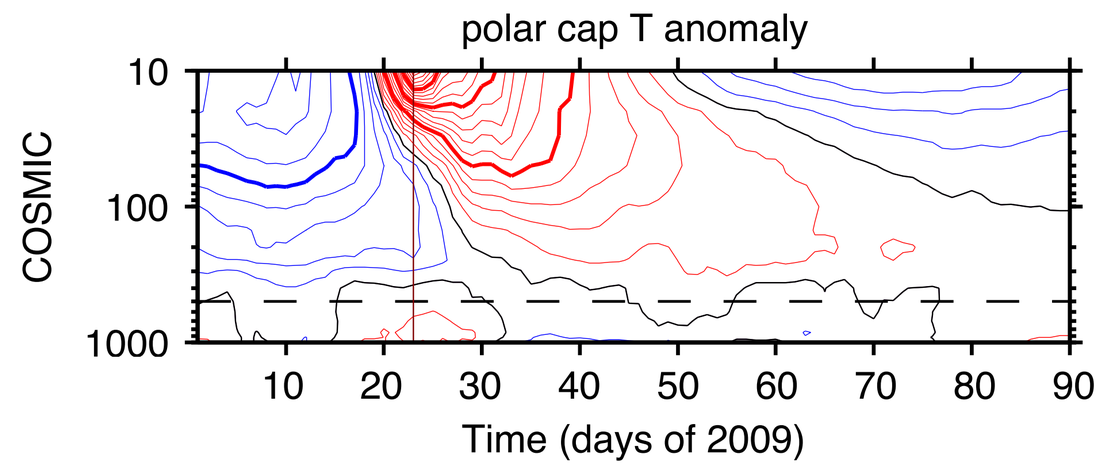


SSW 2009: COSMIC GPS RO Observations

10-hPa Temperature



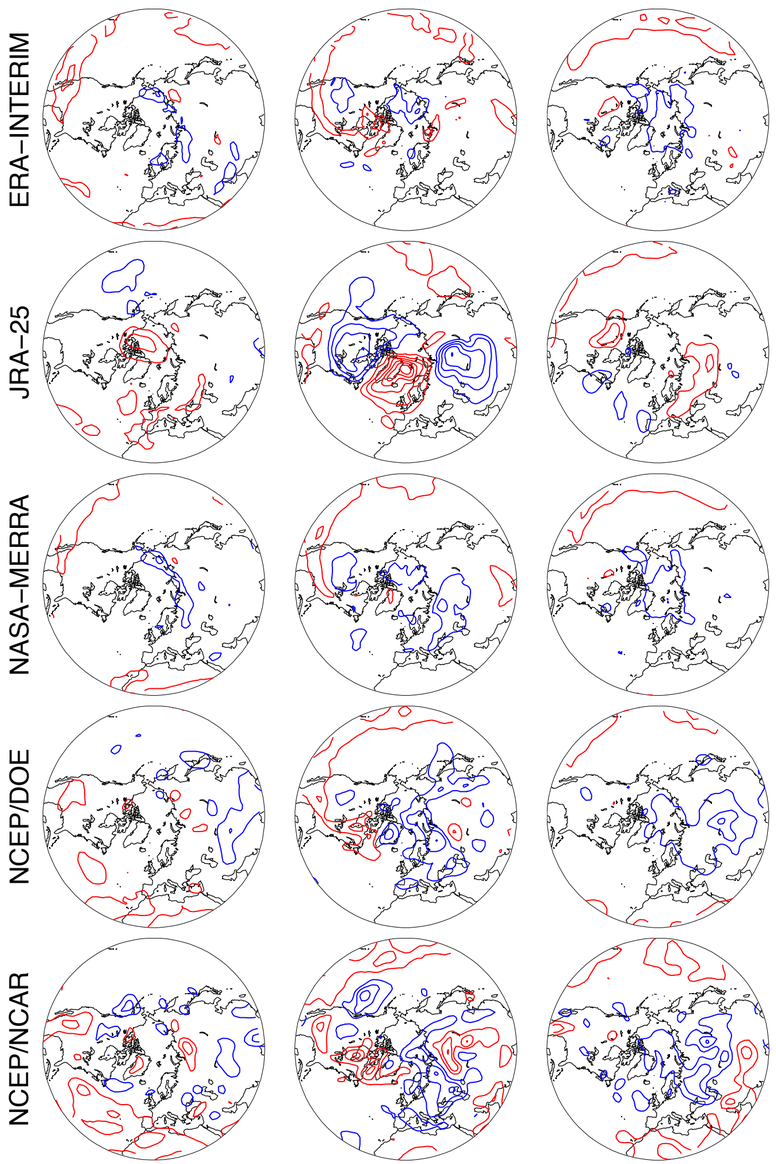
Polar-Cap Temperature Anomalies



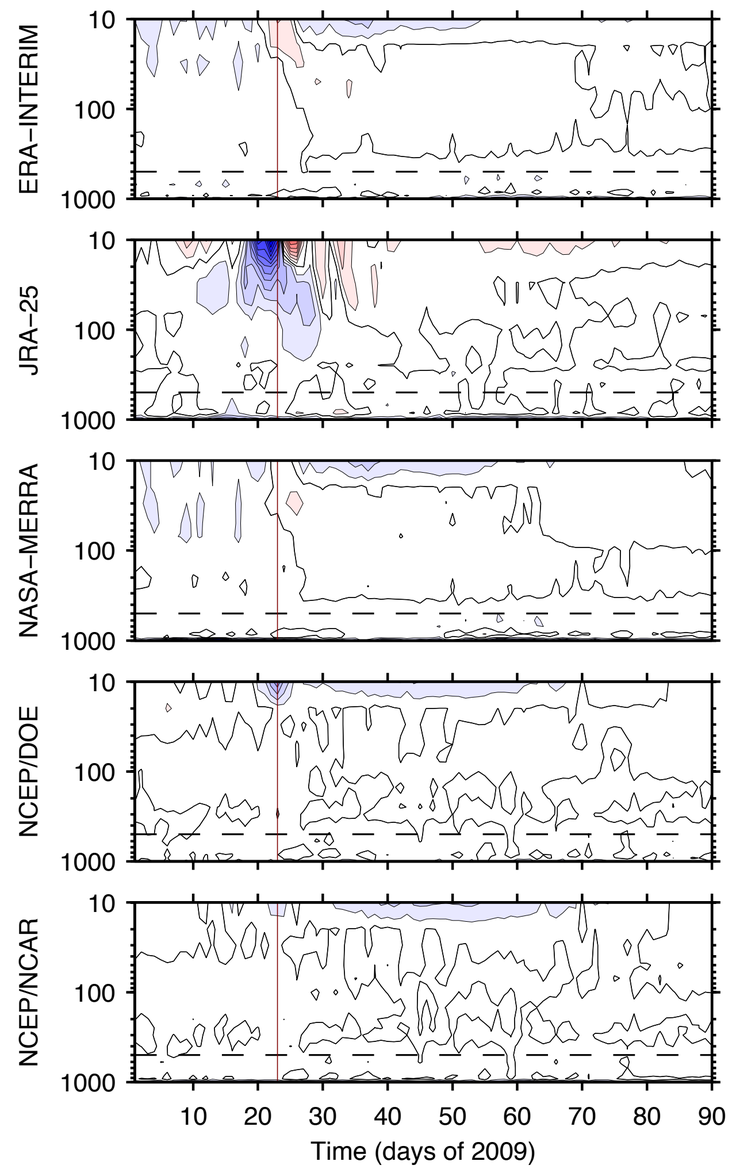
From Martineau and Son (2010)

SSW 2009: Biases of Reanalyses

10-hPa Temperature



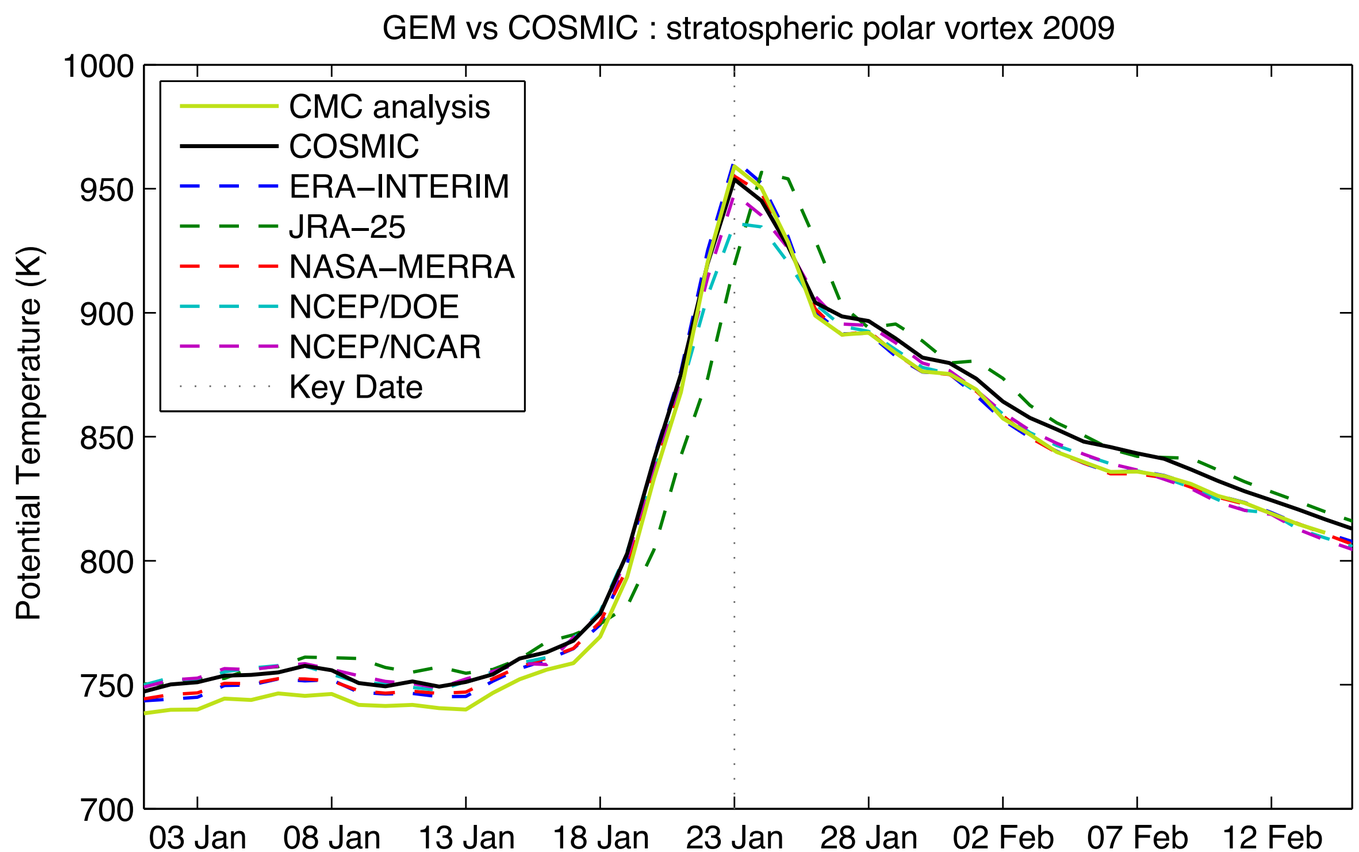
Polar-Cap Temperature Anomalies



All data except the JRA-25 show reasonably small biases (Martineau and Son 2010).

SSW 2009: Biases of Reanalyses

10-hPa Polar-Cap Potential Temperature

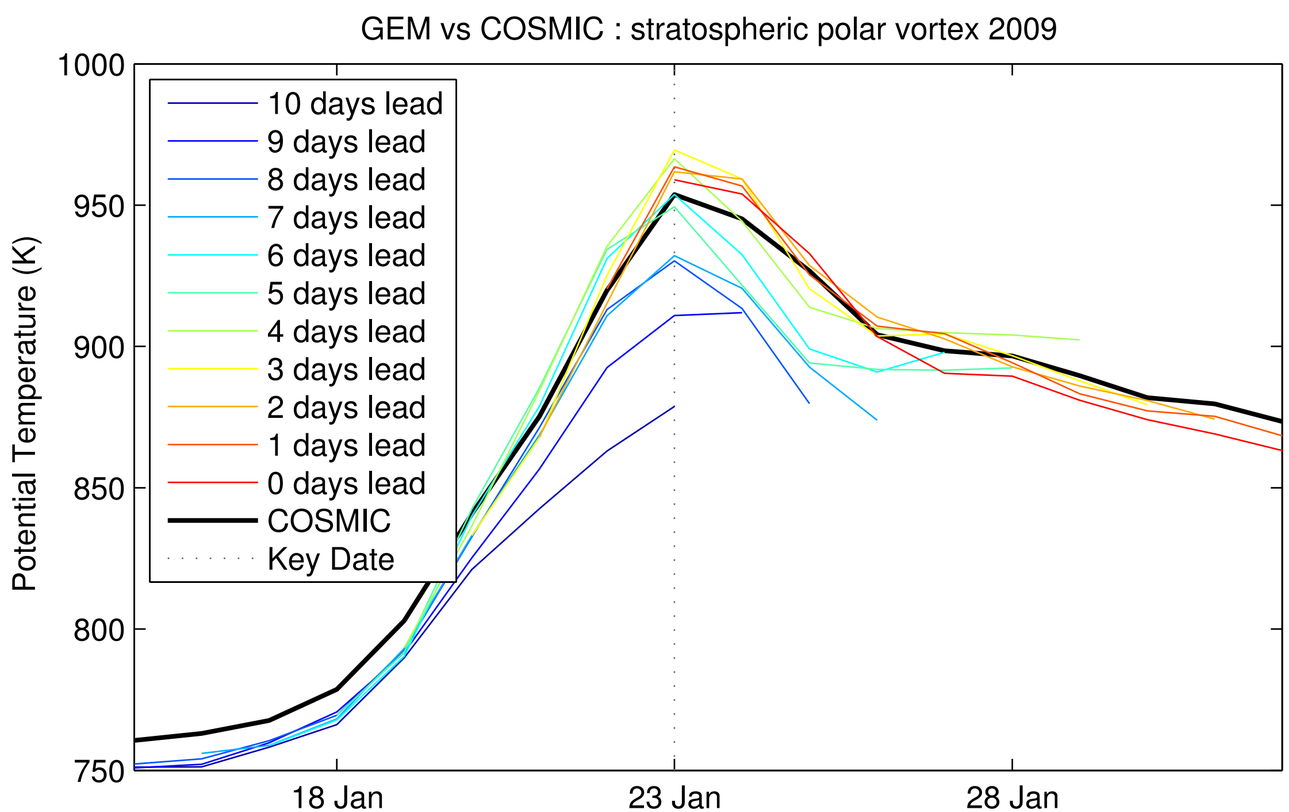


(CMC data from Martin Charron)

CMC analysis is even better than the JRA-25 and NCEP/DOE.

SSW 2009: Prediction of GEM-Strato

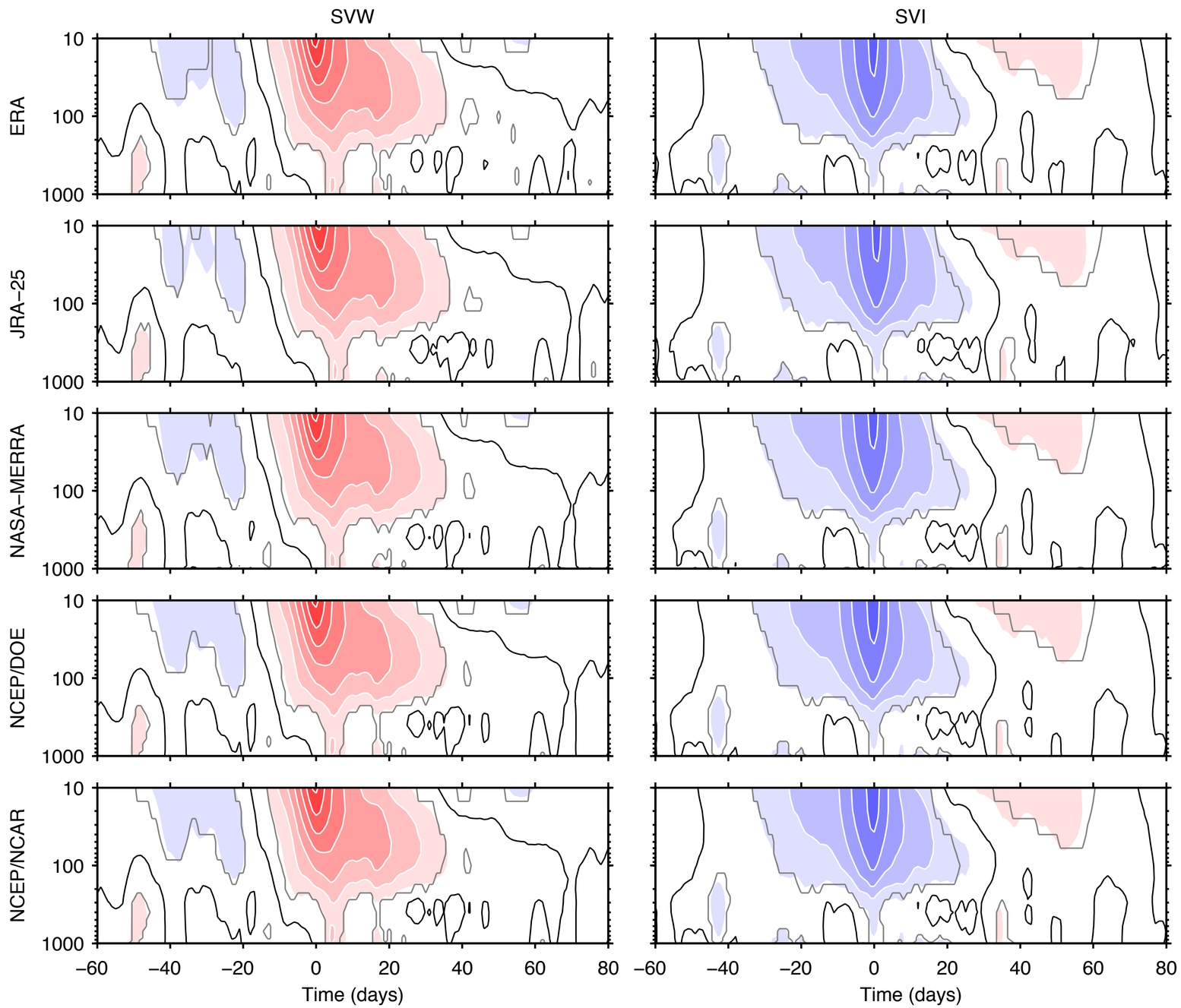
10-hPa Polar-Cap Potential Temperature



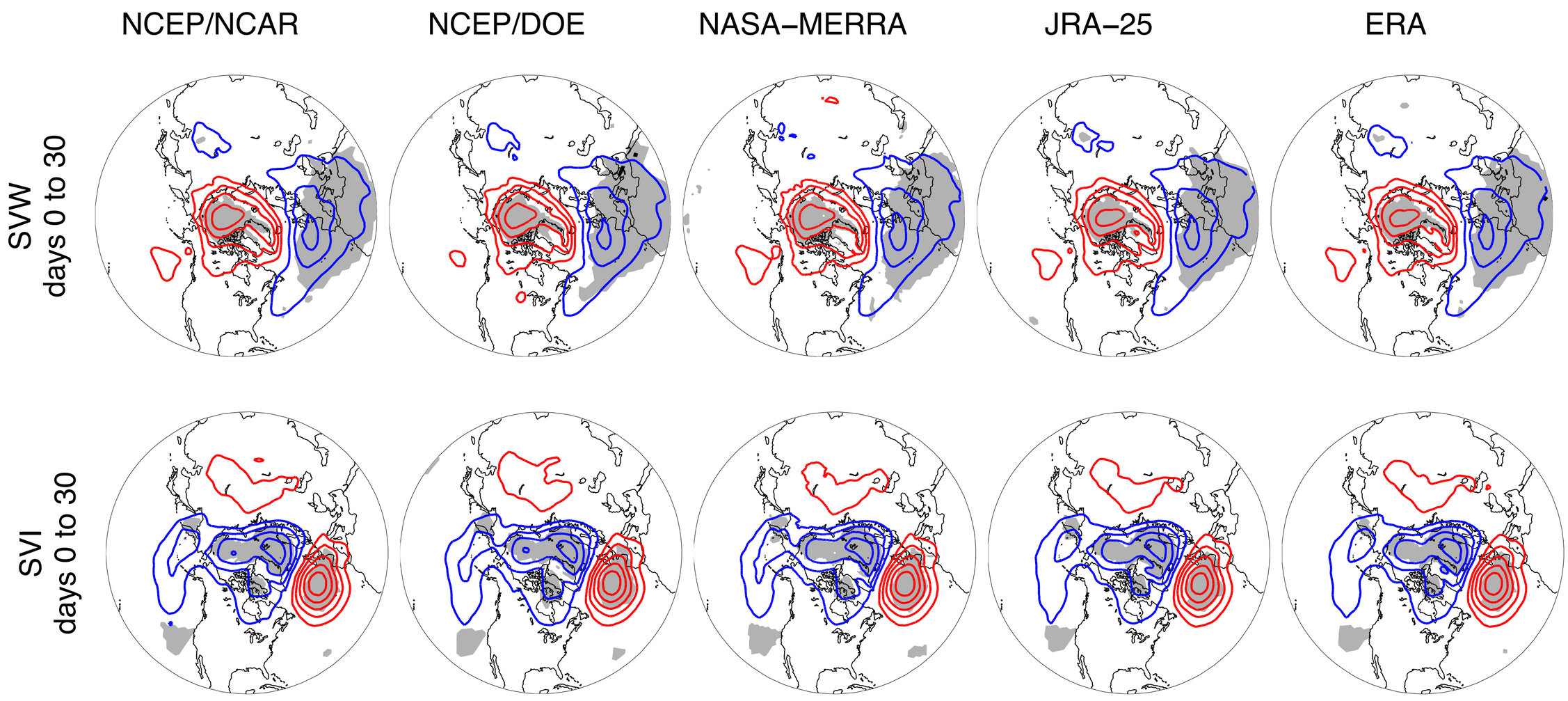
(GEM-Strato data from Martin Charron)

The 10-day forecast captures the SSW. With 6-day lead, it captures even the amplitude of the SSW.

Composite Analysis: NAM-index Anomalies



Composite Analysis: SLP Anomalies



Preliminary Conclusions

- Downward propagation is robustly found in all reanalysis data although the JRA-25 showed delayed SSW during 2009.

- The 2009 SSW event is quantitatively well captured by the CMC analysis. This event is very well predicted by the GEM-Strato with 6-day lead.

- Dynamical mechanism(s) of the downward propagation associated with the SSW and SVI is under investigation.

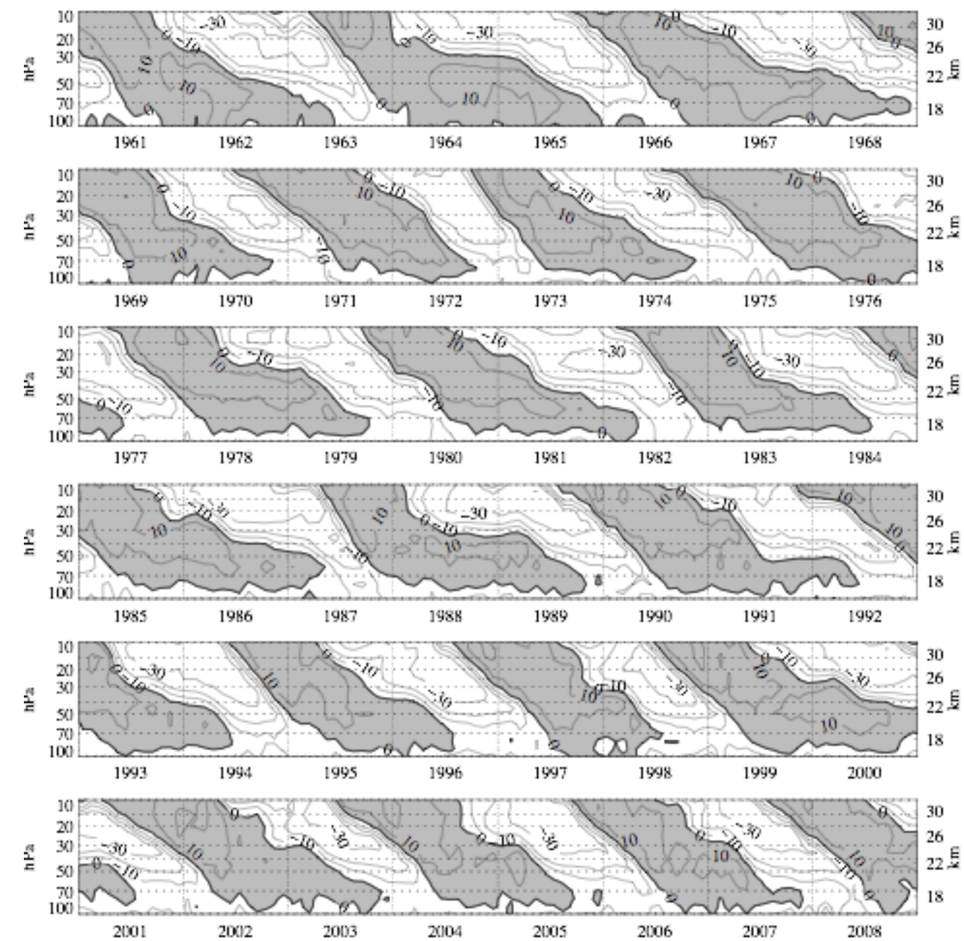
QBO: Impact on the Northern Hemisphere Summer Climate

with H.-S. Kim and H. Lin

QBO: Tropical Stratospheric Phenomena

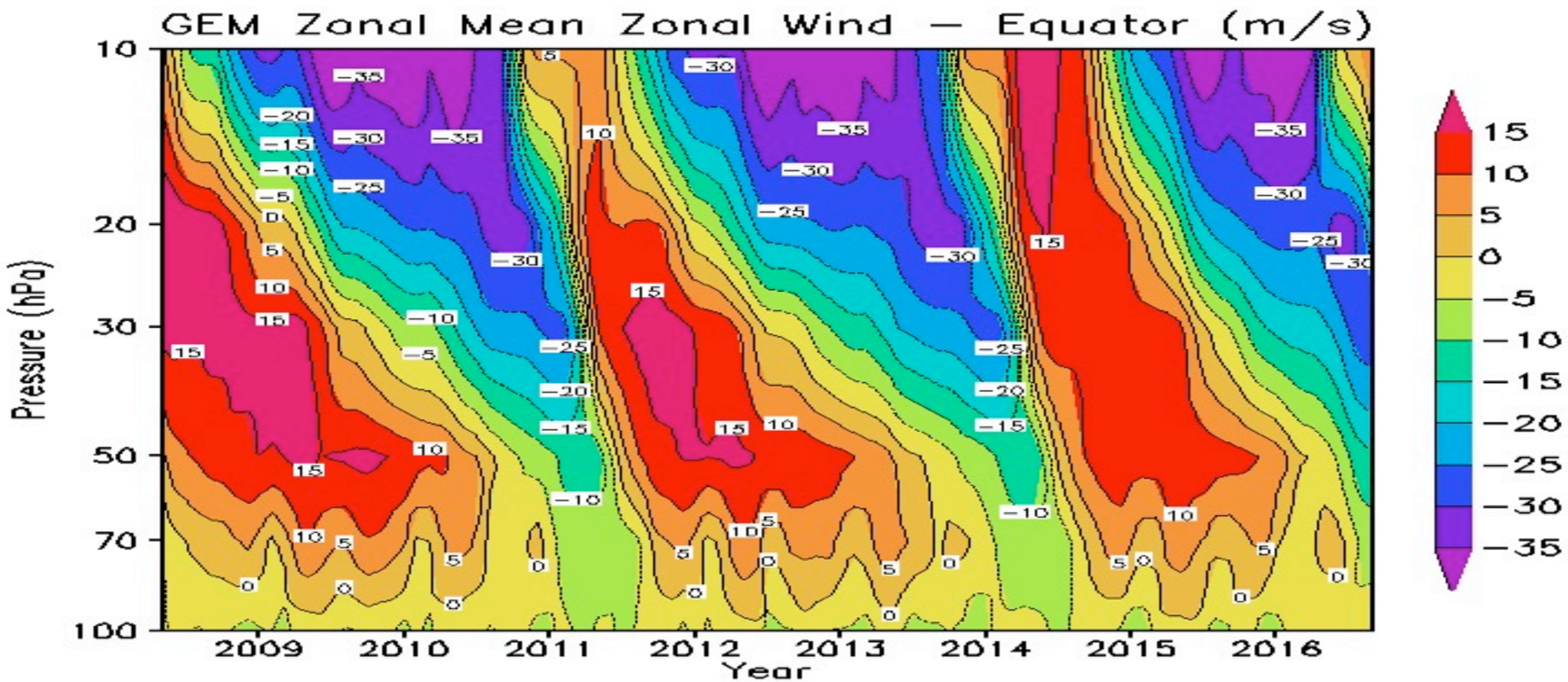
- The zonal wind over the equator changes its sign with a period of ~28 months.
- It propagates downward from ~10 hPa to ~100 hPa (~1 km/month) with a decreasing magnitude.
- The westerly and easterly phases are not symmetry: e.g., westerlies are generally weaker, propagate more rapidly, and persist longer near the tropopause.

[u] at the equator (radiosonde)



Time-height section of monthly mean zonal winds (CI=10 m/s) at the 3 equatorial radiosonde stations. Updated from Naujokat (1986) by Freie Universitat (http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/).

QBO: QBO in GEM-Strato

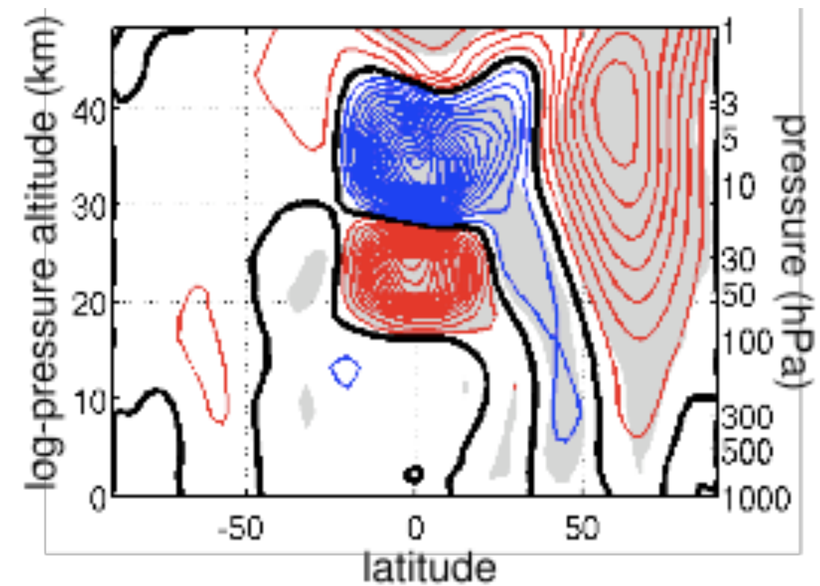


Courtesy of Hai Lin

QBO: Extratropical Stratospheric Response

Holton-Tan effect (Holton and Tan, 1980): The QBO can change the wave propagation in the NH stratosphere: equatorward propagation during the WQBO, resulting in stronger westerly in the extratropical stratosphere or positive NAM index.

Nov.-Dec. [u] anomaly (ERA40)



From Anstey and Shepherd (2008)

QBO: Tropospheric Response

Stratospheric Path

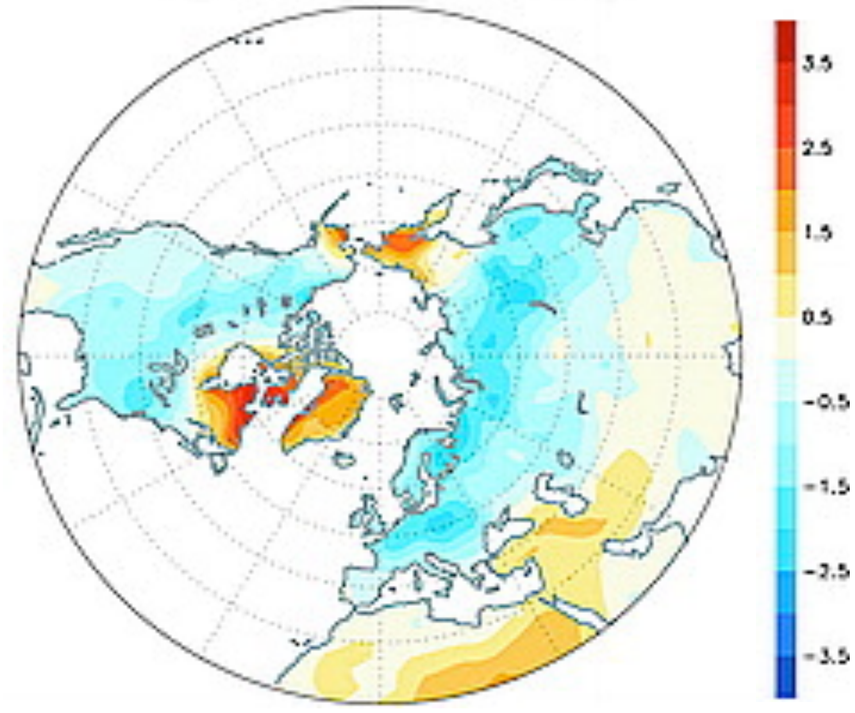
- QBO modifies the polar vortex (Holton-Tan effect). The associated anomalies propagate downward to the surface.

EQBO at 50 hPa -> Weak polar vortex -> Negative NAM index

- It could occur only in the NH winter.

January SAT anomalies

QBO easterly-westerly



From Thompson et al. (2002)

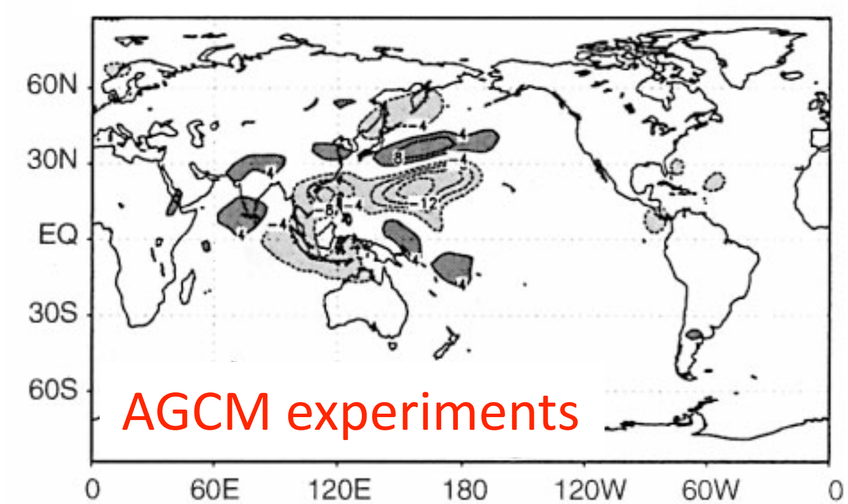
QBO: Tropospheric Response

Tropospheric Path (?)

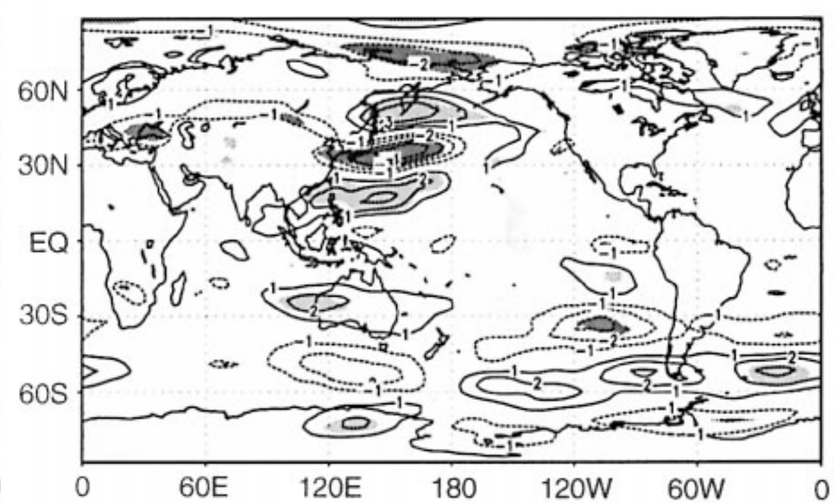
- QBO could modify deep convection in the tropics (Giorgetta et al. 1999; Collimore et al. 2003). The associated heating may generate Rossby wave train, affecting the NH summer circulation. Gray (1984) and Chan (1995) suggested that Hurricane/Typhoon activities are modulated by the QBO.

QBO -> Tropical convection -> Rossby wave trains/ Hurricanes

JJA OLR (EQBO-WQBO)



JJA 500-hPa U (EQBO-WQBO)



AGCM integrations with prescribing EQBO and WQBO winds in the tropics (Giorgetta et al. 1999)

Researches at McGill

Researches at McGill

- **Does the QBO influence the NH summer circulation in the real atmosphere?** We examine the QBO-related circulation change in the ERA40 reanalysis data.

- **Is the QBO-induced circulation changes associated with tropical convection? If it is, how does the QBO modify tropical convections?** We extend numerical analyses of Giorgetta et al. (1999) and Collimore et al. (2003) by using the OLR, precipitation and ERA40 data.

- **Does the QBO affect Typhoon activities?** We revisit QBO-Hurricane relationship which has been discarded in 90s'.

Data

ERA40

- Monthly mean data from **1958 to 2002**
- Only **June-October (JJASO)**, Hurricane/Typhoon season, are used.

ORL and SST

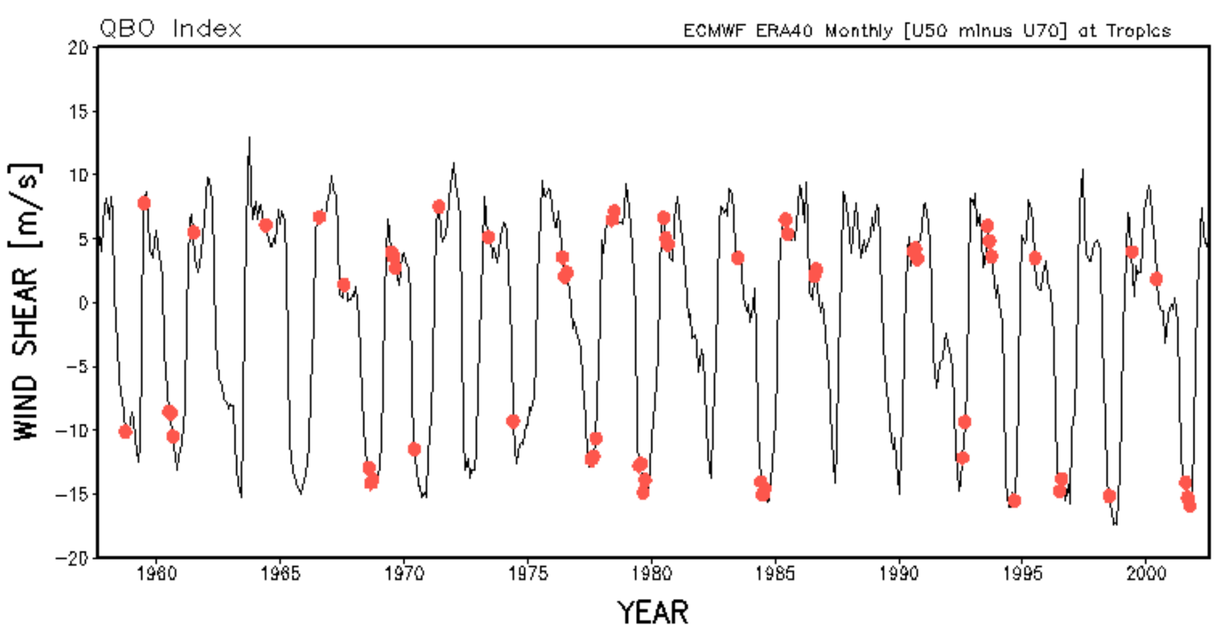
- **NOAA OLR** from 1974 to 2002, except 1978 when data is not available
- **ERSSTv3 SST** from 1974 to 2002, except 1978

Precipitation

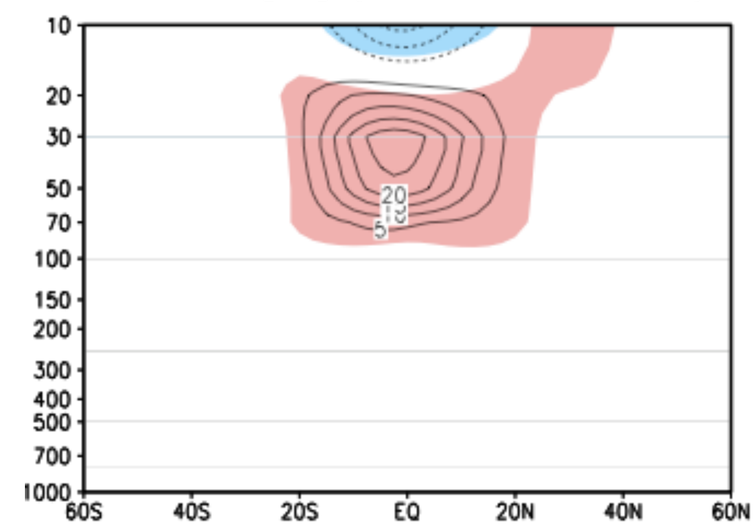
- **CMAP** precipitation from 1979 to 2002

Data

- **QBO index = $[u]_{50hPa}$ - $[u]_{70hPa}$** (Huesmann and Hitchman, 2001)
- Exclude ENSO years by picking the months of |NINO3.4| < 0.5 std
- **WQBO** = QBO index anomaly > 0.5 std. (**32 months**)
- **EQBO** = QBO index anomaly < -0.5 std. (**28 months**)
- Differences, **WQBO-EQBO, are shown** with shading for significant values.

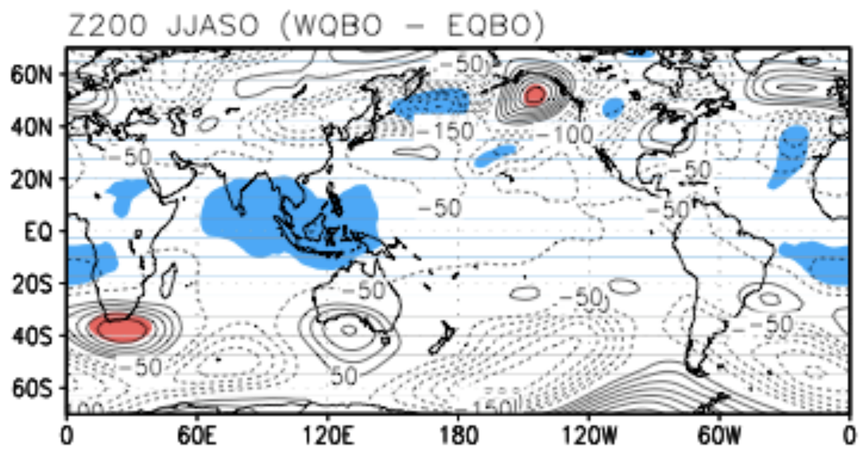


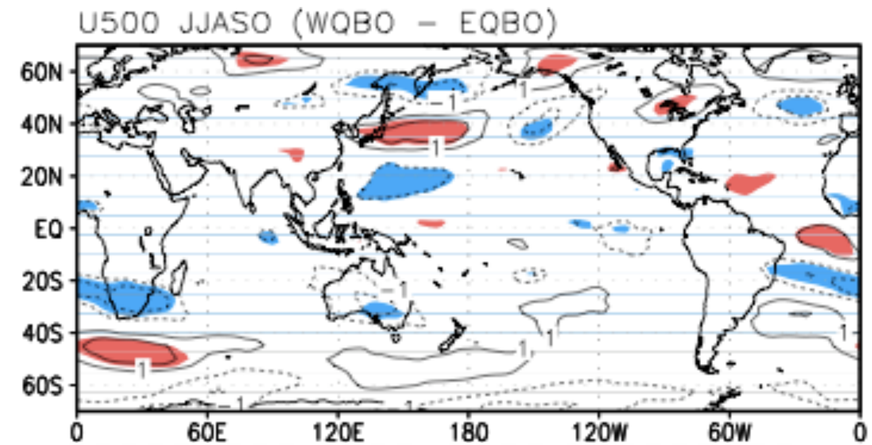
JJASO [U] (WQBO-EQBO)

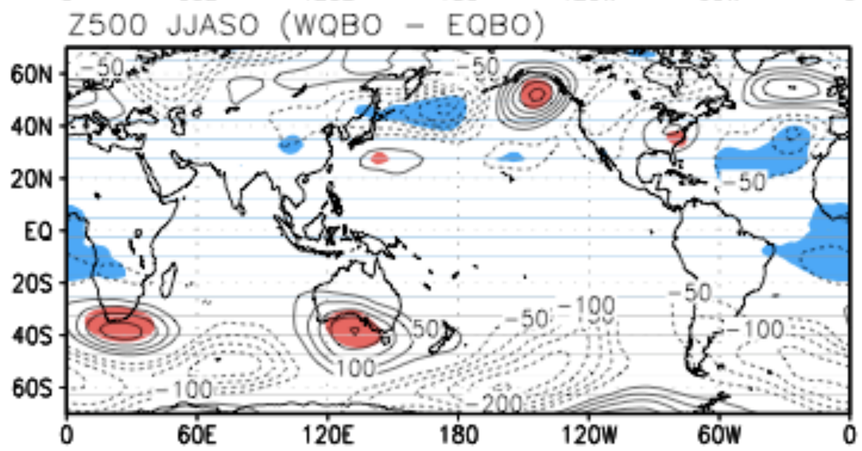


Results: QBO vs. Extratopical Circulations

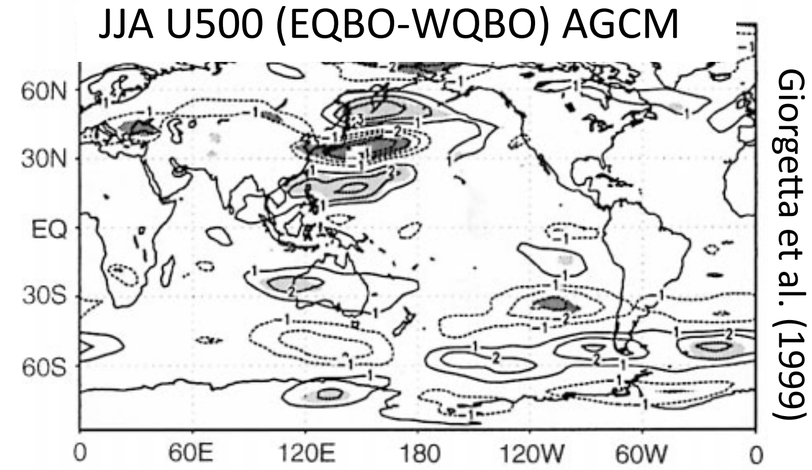
Q. Does the QBO influence the NH summer circulations?







JJA U500 (EQBO-WQBO) AGCM



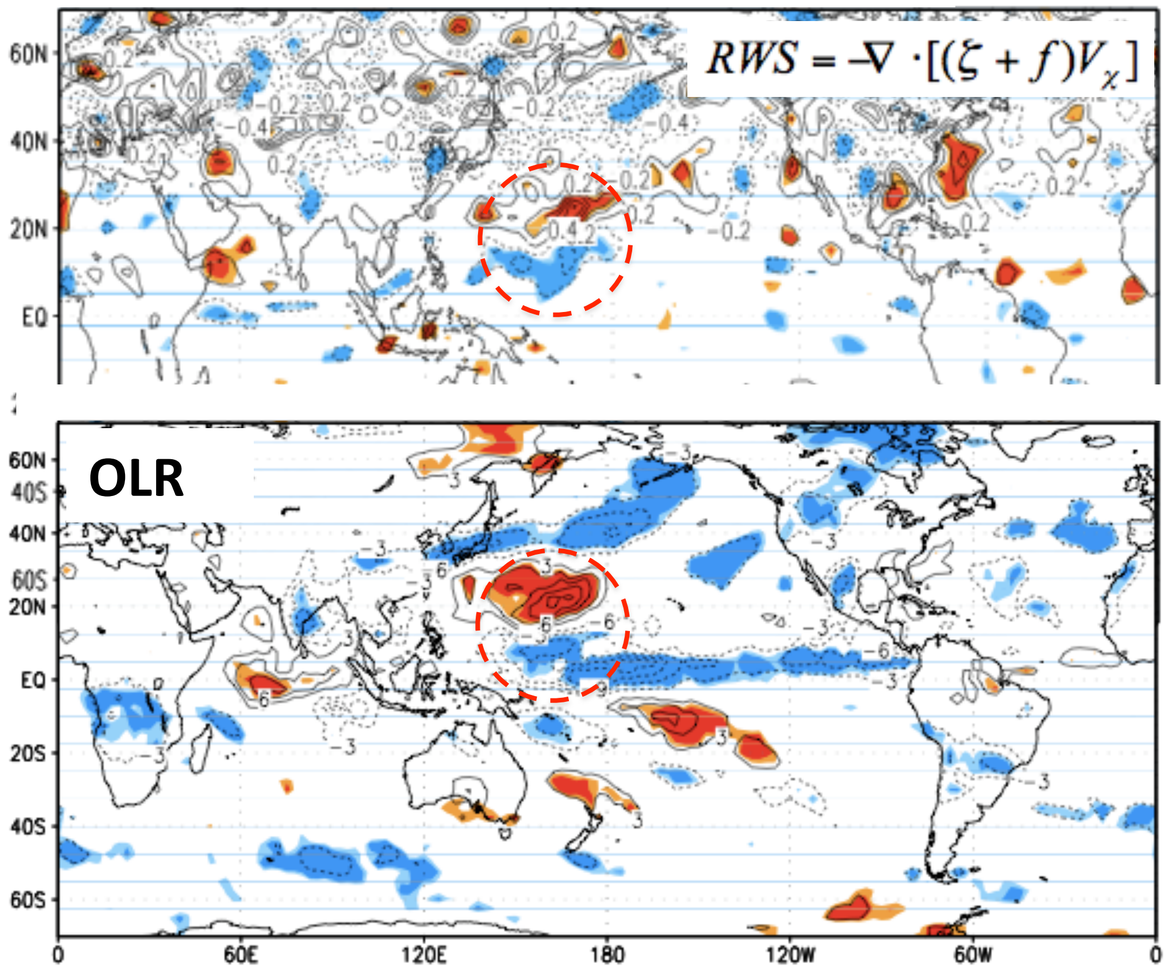
Giorgetta et al. (1999)

Yes. The QBO-induced circulation in the ERA40 is very similar to that in the AGCM experiments by Giorgetta et al. (1999)

Results: QBO vs. Extratopical Circulations

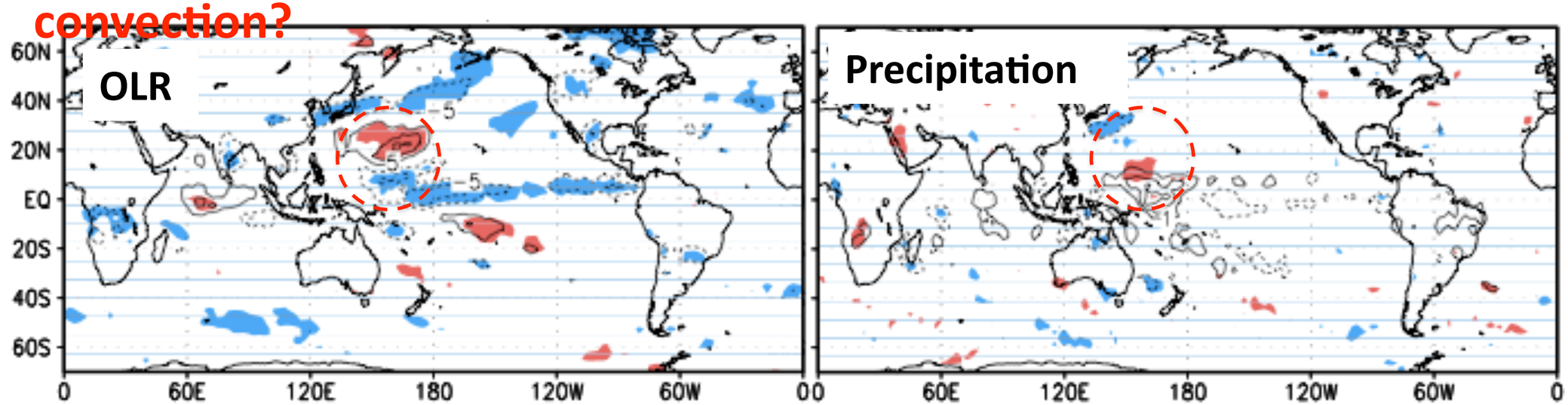
Q. Is the QBO-induced circulation changes associated with the convection?

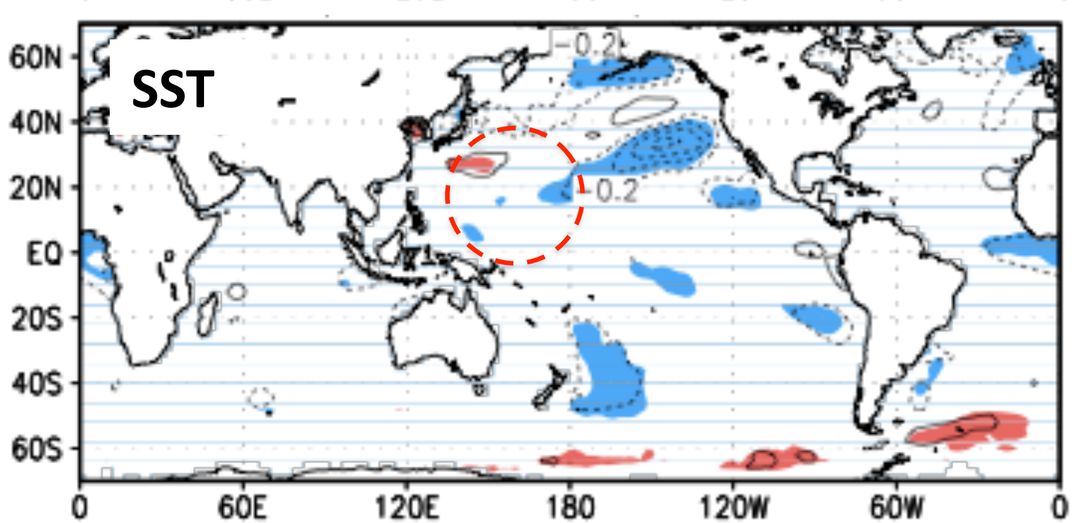
Rossby Wave Source (RWS)



Results: QBO vs. Extratopical Circulations

Q. Is the QBO-induced circulation changes associated with the convection?



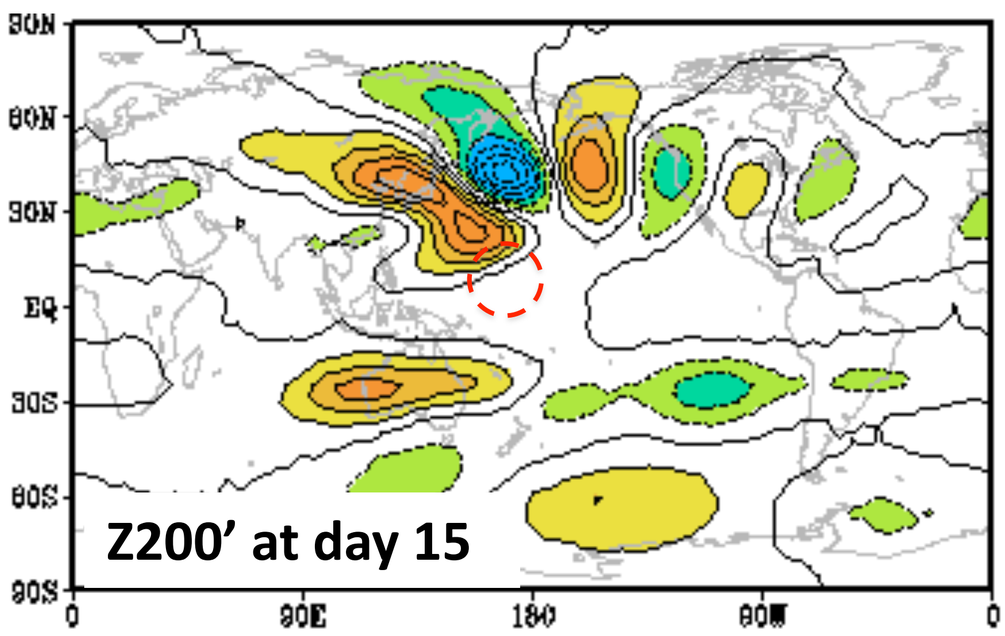


Yes. Rossby wave train is associated with tropical deep convections.

Results: QBO vs. Extratopical Circulations

Q. Is the QBO-induced circulation changes associated with the convection?

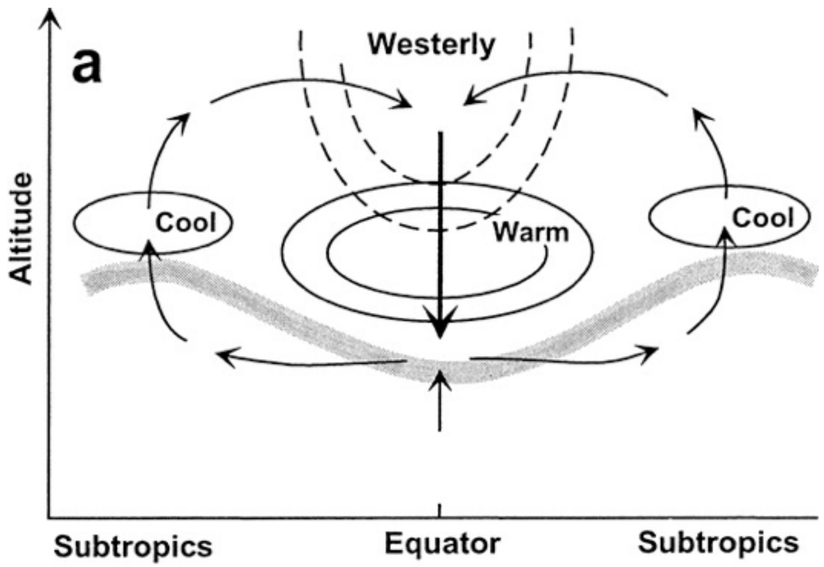
- A series of simple model experiments, essentially same to Jin and Hoskins (1995), are performed with a primitive equation model of T31L10 (Lin, 2010): e.g., **A gaussian-shaped heating is turned on at 10N 170E for a JJASO background flow**.
- Model is integrated up to 20 days. The result, which is essentially **a linear response** to the heating, shows **strong similarity** to the observations



- It further confirms that the QBO-related Z200 anomalies are largely driven by tropical convection.

Results: QBO vs. Tropical Convection

Q. How does the QBO modify tropical deep convection (at 10°N 170°E)?



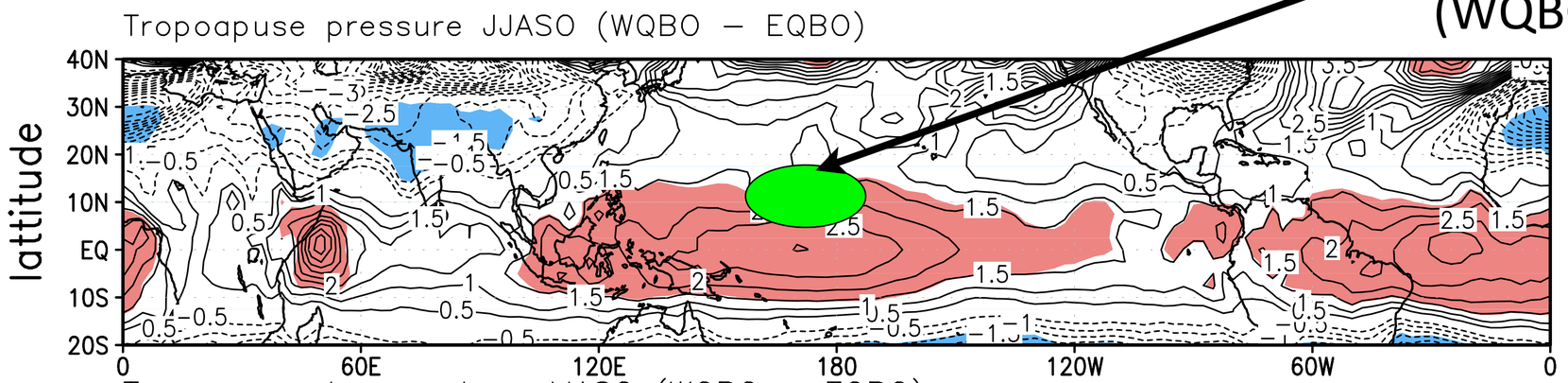
From Collimore et al. (2003)

- Lower Tropopause height (or higher tropopause pressure) could lead to weaker deep convection (Reid and Gage 1985; Gray et al. 1992)
- Warm tropopause and associated increase in static stability could lead to weaker deep convection (Gray et al. 1992)
- Weaker absolute vertical wind shear in the UTLS could lead to stronger deep convection (Gray et al. 1992; Collimore et al. 2003)
- Stronger horizontal vorticity (or weaker anticyclonic vorticity) in the UTLS could lead to weaker deep convection (Collimore et al. 2003)

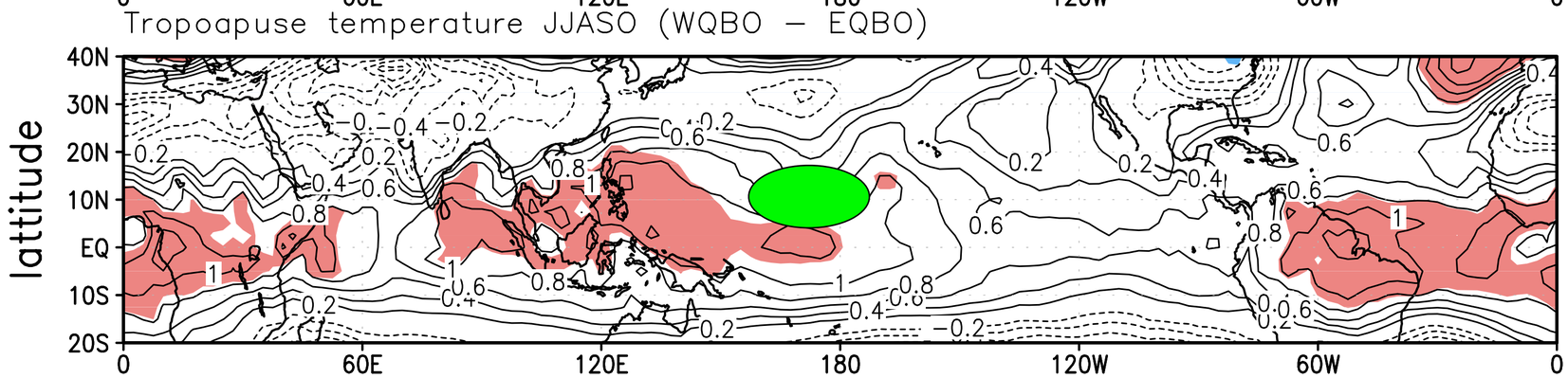
Results: QBO vs. Tropical Convection

Enhanced Convection
(WQBO-EQBO)

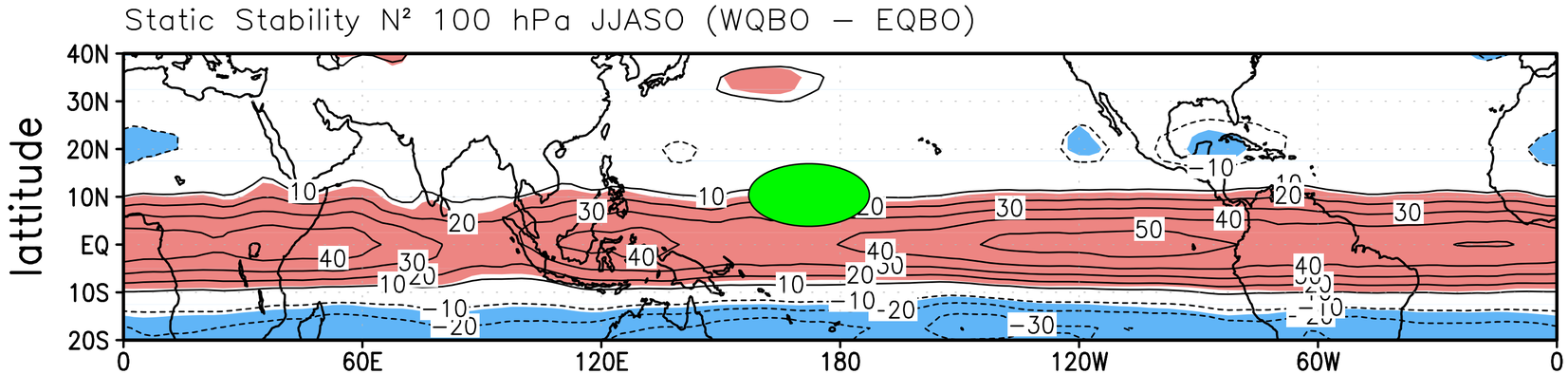
TRP
Pressure



TRP
Temp.



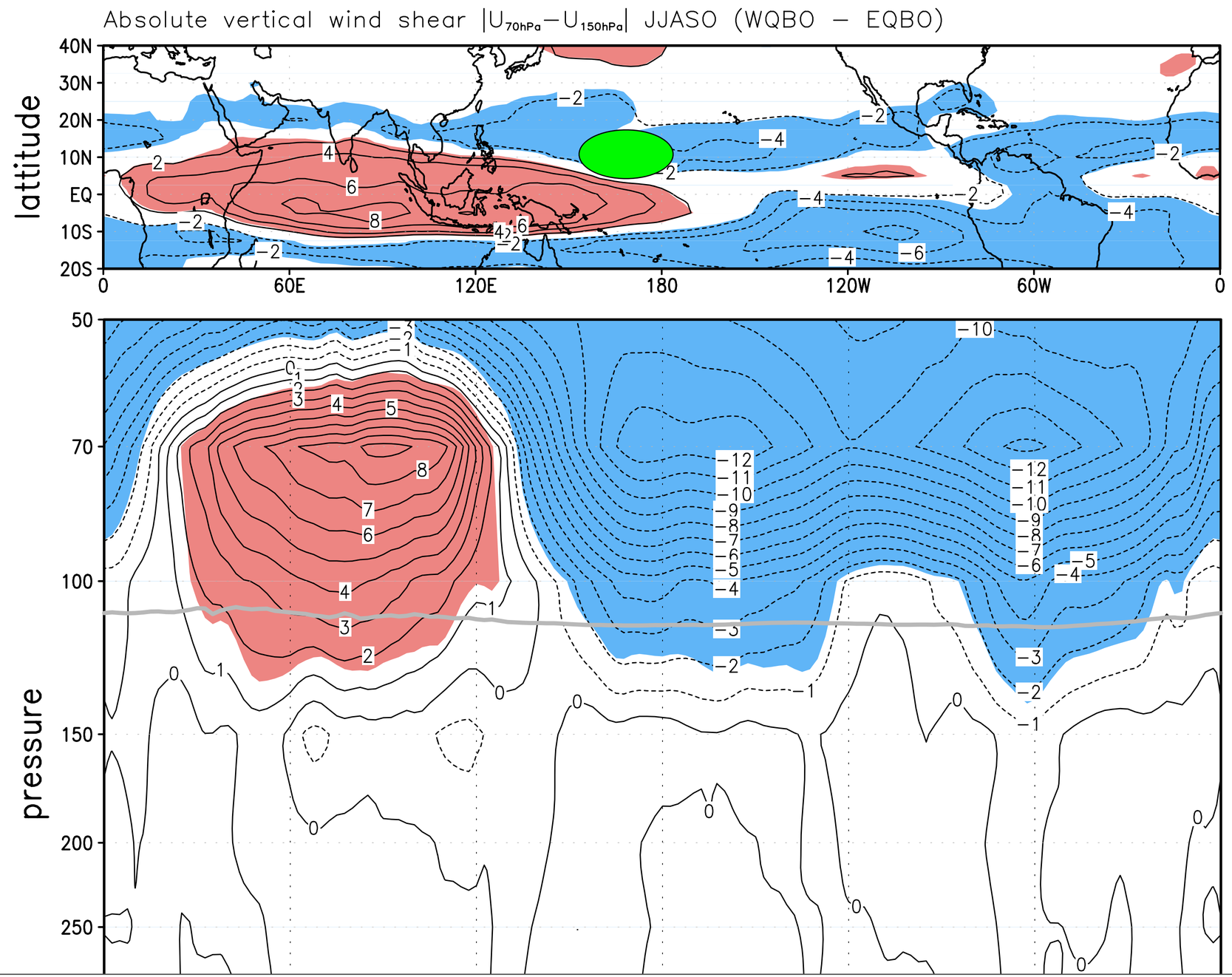
N^2 at
100 hPa



Results: QBO vs. Tropical Convection

Wind Shear 70-150hPa

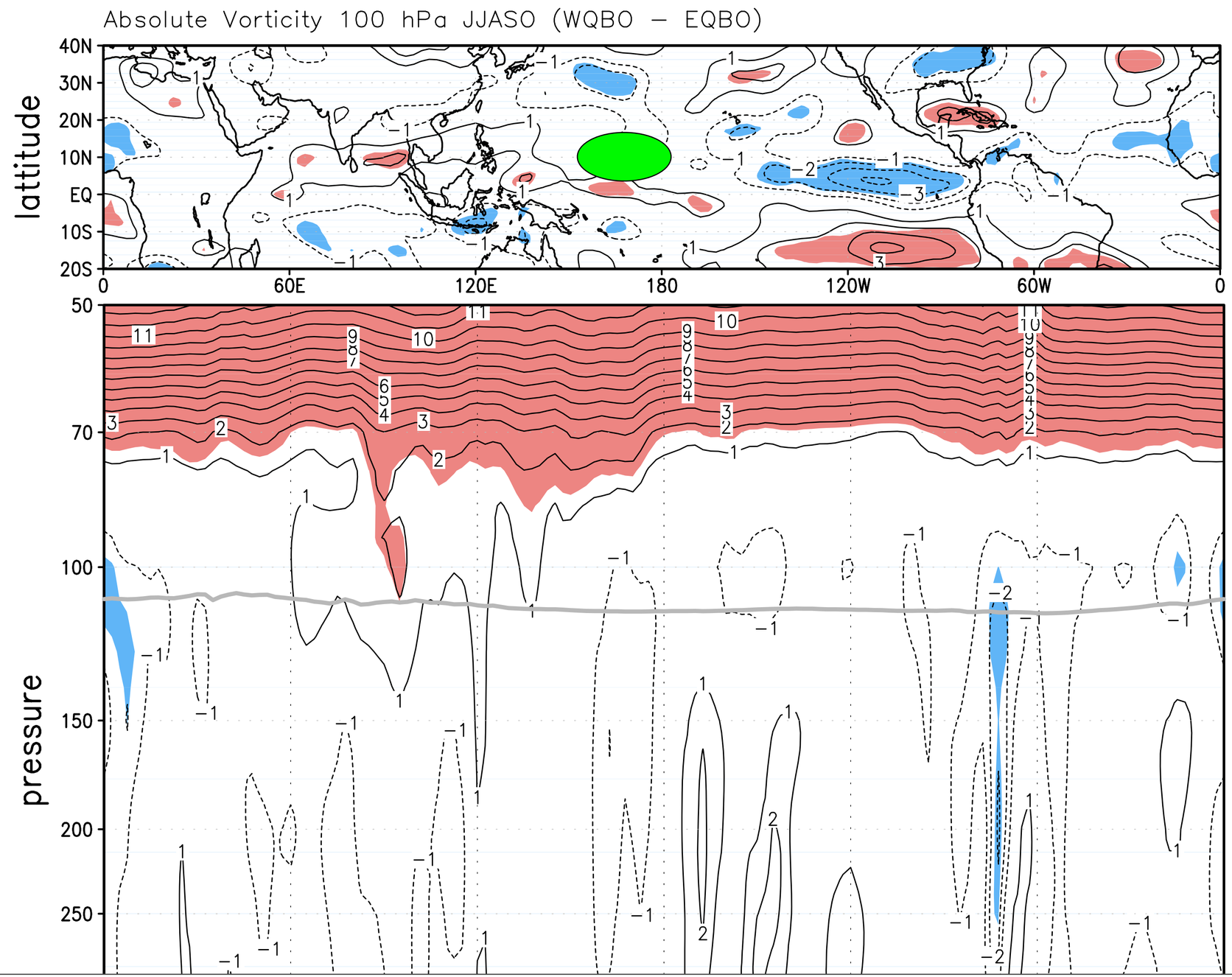
Wind Shear at 10N



Results: QBO vs. Tropical Convection

Absolute Vorticity at 100hPa

Absolute Vorticity at 10N



Results: QBO vs. Tropical Convection

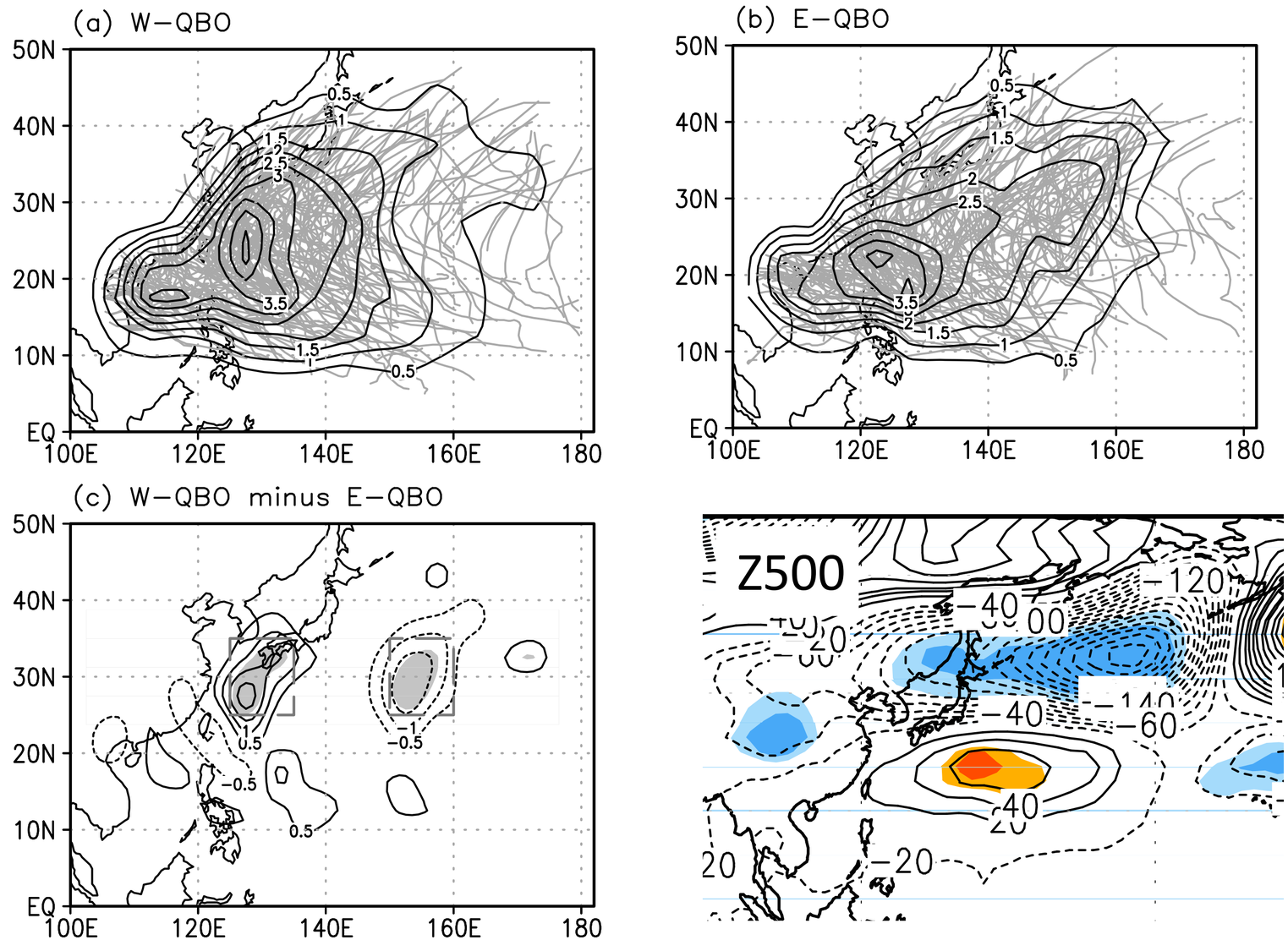
Q. How does the QBO modify tropical deep convection (at 10°N 170°E)?

Weakened vertical wind shear likely leads to stronger deep convection (Gray et al. 1992; Collimore et al. 2003).

- Lower Tropopause height (or higher tropopause pressure) could lead to weaker deep convection (Reid and Gage 1985; Gray et al. 1992)
- Warm tropopause and associated increase in static stability could lead to weaker deep convection (Gray et al. 1992)
- Stronger horizontal vorticity (or weaker anticyclonic vorticity) in the UTLS could lead to weaker deep convection (Collimore et al. 2003)

Results: QBO vs. Typhoon

Q. Does the QBO affect Typhoon activities?

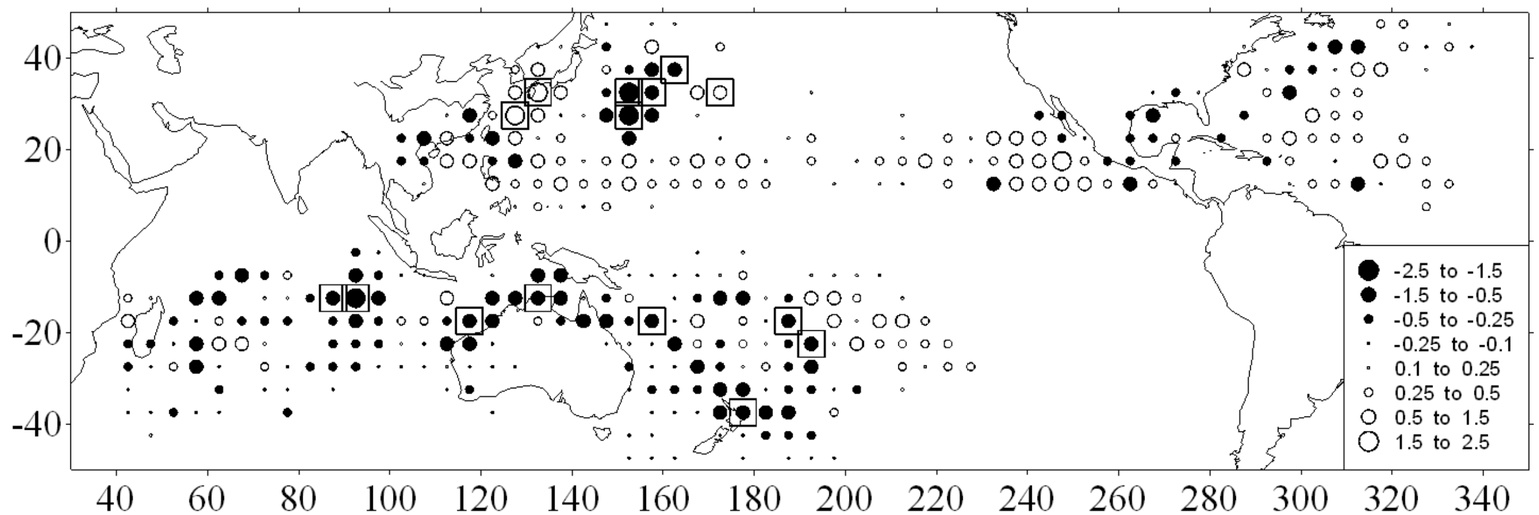


From Ho et al. (2009)

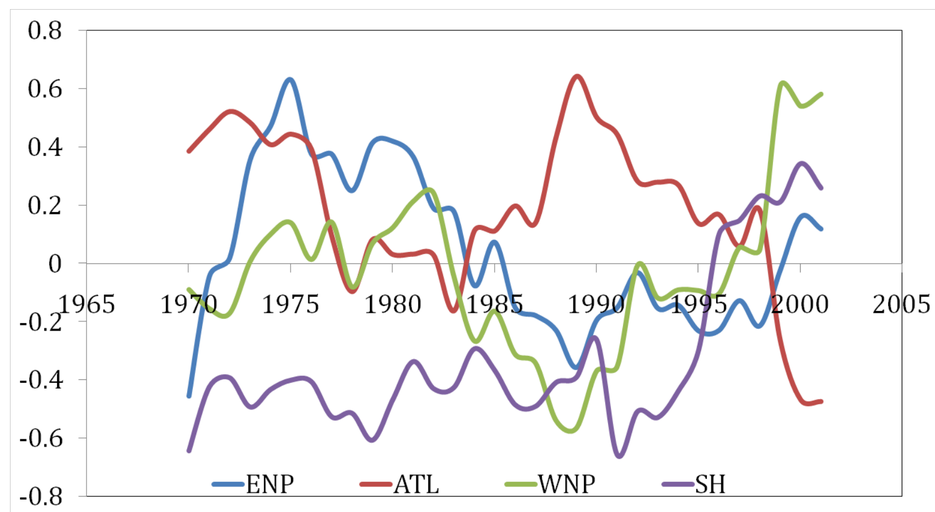
Yes. the QBO can change the Typhoon track over the Western North Pacific.

Results: QBO vs. Typhoon

WQBO-EQBO: NH JJAS and SH DJFM hurricane passage numbers



11-year moving correlation between Hurricane genesis and QBO index correlation



Conclusions

- **Does the QBO influence the NH summer circulation in the real atmosphere? Yes**, the NH circulation shows quasi-barotropic response with Rossby-wave train pattern.

- **Is the QBO-induced circulation changes associated with tropical convection? Yes**, enhanced convection at 10N 170E is responsible for wave train pattern. **If it is, how does the QBO modify tropical convections? Presumably by weakening vertical wind shear** in the UTLS. The detailed investigations, using numerical models such as cloud-resolving models, are needed to quantitatively evaluate the mechanism.

- **Does the QBO affect typhoon activities? Yes**, the QBO affects the Northwestern Pacific typhoon tracks. No impact however is found to the North Atlantic hurricane activities.

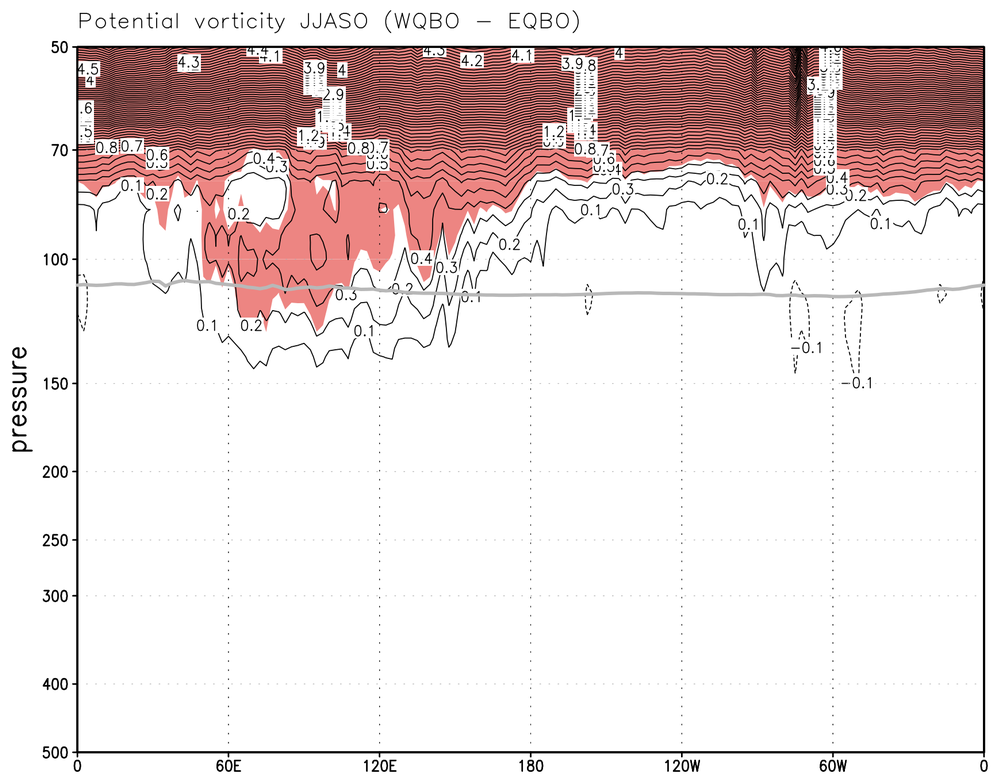
Ozone Hole: visit my personal website
http://www.meteo.mcgill.ca/~swson/

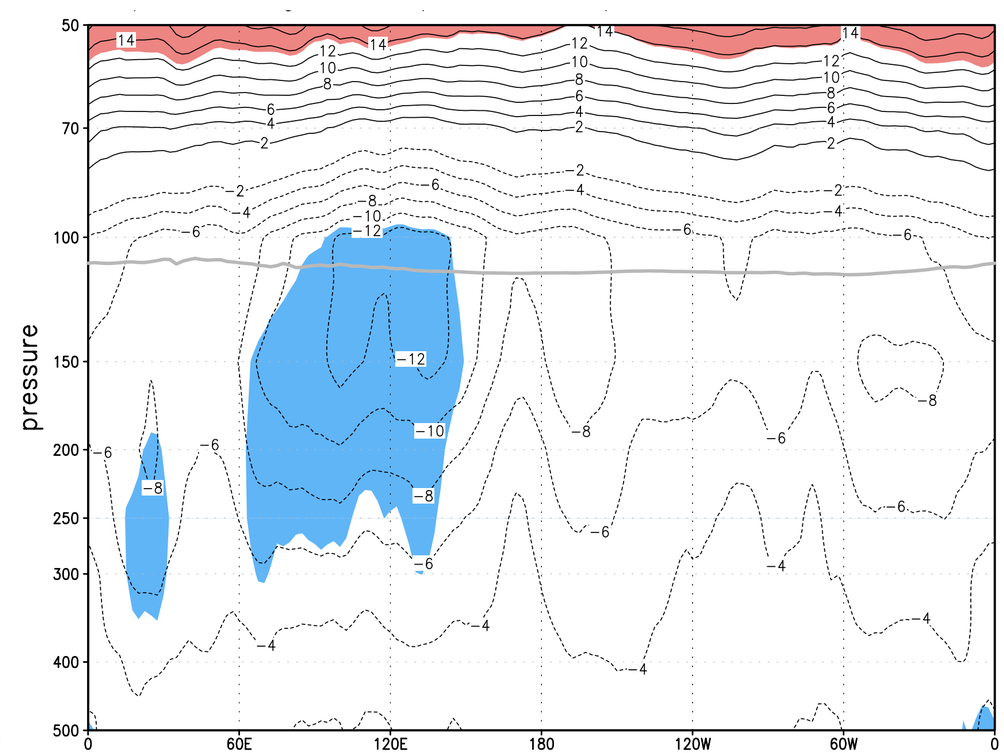
Thank You!

Results: QBO vs. Tropical Convection

Q. How does the QBO modify tropical deep convection (at 10°N 170°E)?

- Other possibility?: localized high PV in the UTLS could lead to stronger updraft and stronger convection on its east side in the presence of positive wind shear (Hoskins et al. 1985).





Composite Analysis

10-hPa NAM-index anomalies