Is the Trend in Tropical Cyclone Formation Frequency due to Global Warming?

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"Limiting warming to 1.5°C is possible within the laws of chemistry and physics but doing so would require unprecedented changes"

(Jim Skea, Co-Chair of IPCC Working Group III)

Global Warming of 1.5°C

An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

Headline Statements from the Summary for Policymakers*

Understanding Global Warming of 1.5°C

Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*)

Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are unlikely to cause global warming of 1.5°C (*medium confidence*).

https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/sr15_headline_statements.pdf

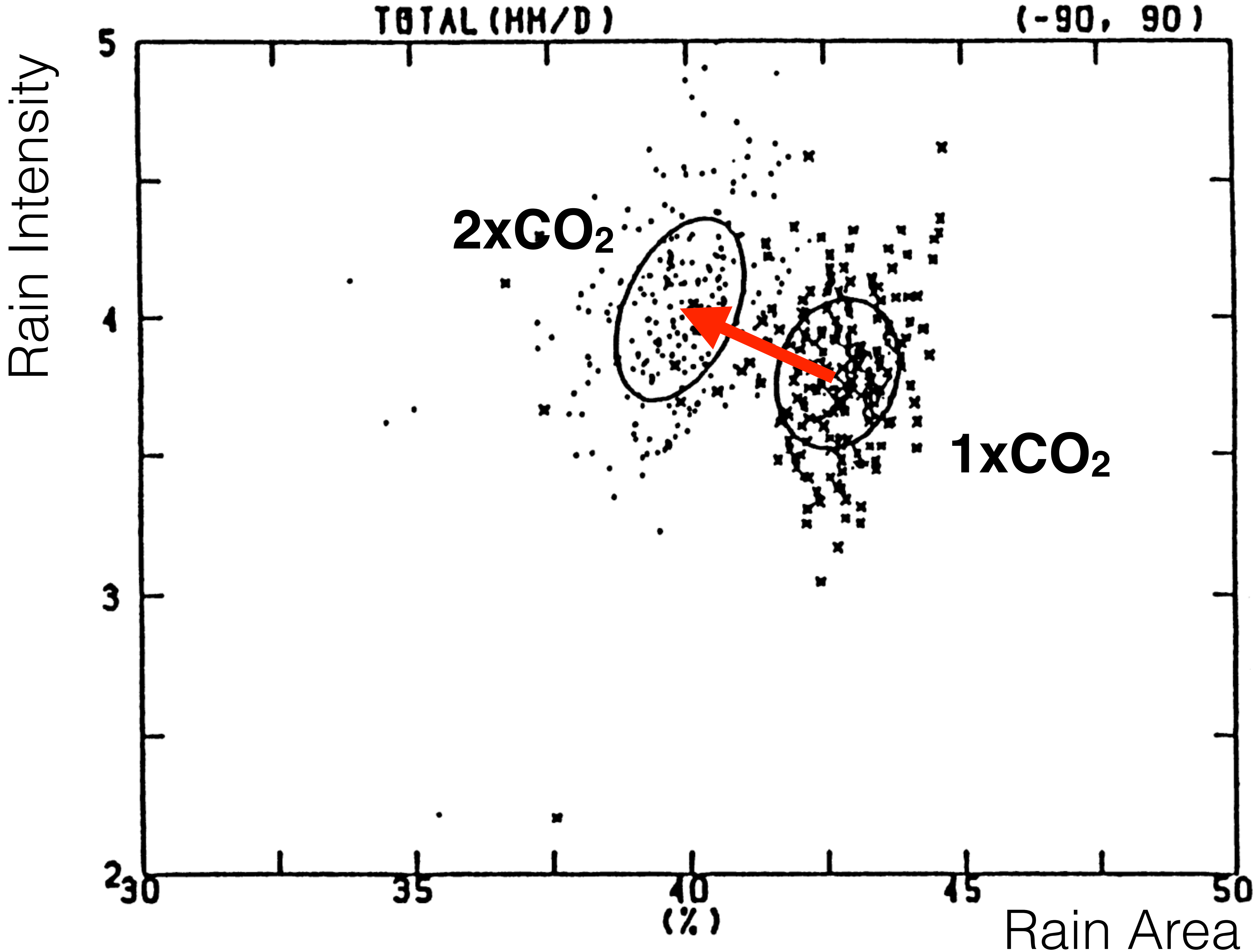
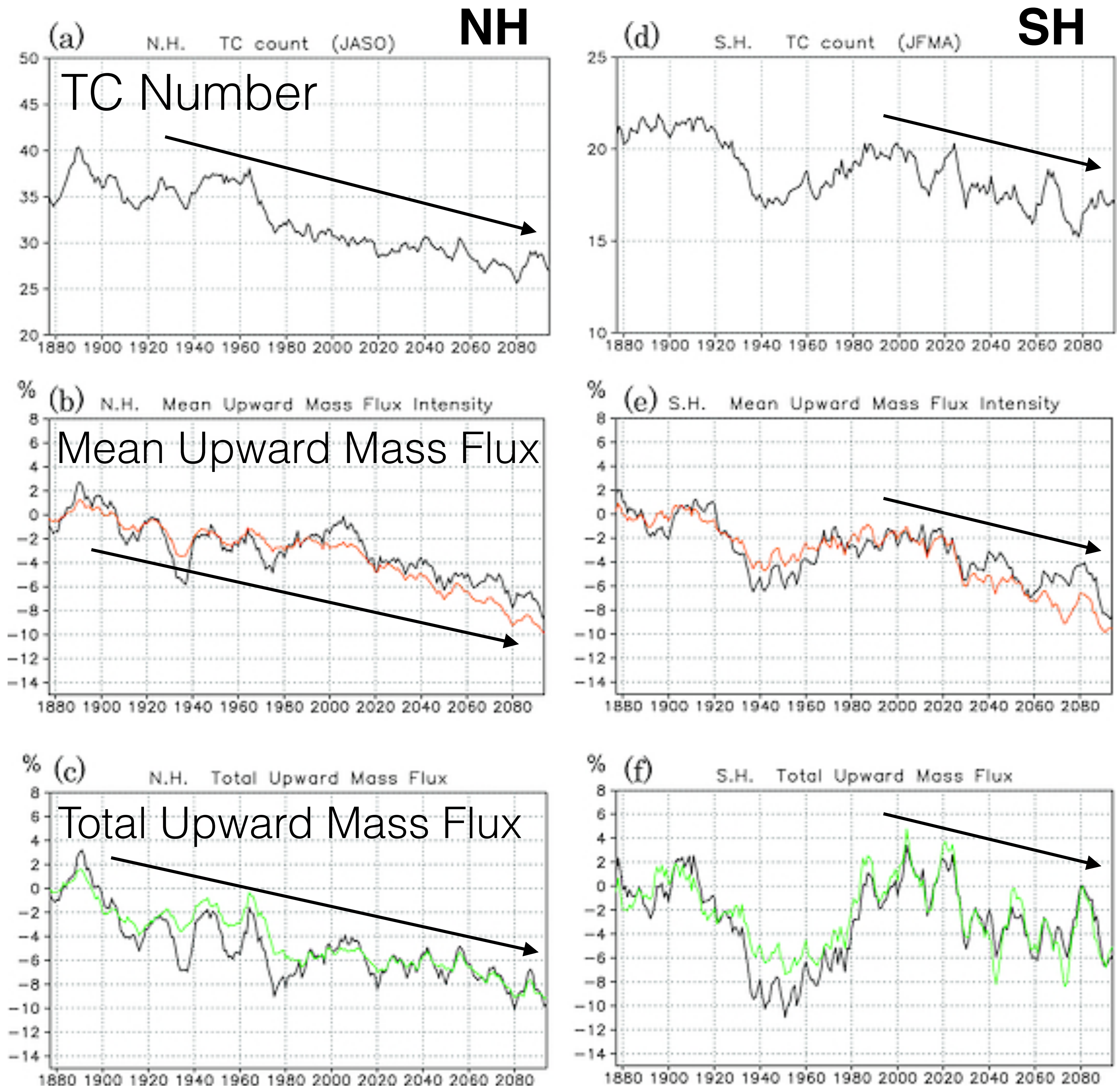


Fig. 1. Scatter diagram of the precipitation rate (mm/day) versus the ratio (%) of the precipitation grid area to the global domain for January 1 to 10. Ellipses drawn with thick solid line and thin solid line denote the root mean square scattering for $1 \times CO_2$ and $2 \times CO_2$, respectively. Data points for $1 \times CO_2$ and $2 \times CO_2$ are denoted by crosses and dots, respectively (Noda and Tokioka, 1989).

Future Projections of tropical cyclone activity

- Oouchi et al. (2006): Using 20 km resolution AGCM simulation, tropical cyclone frequency **decreased** 30% globally (but increased about 34% in the North Atlantic). The strongest tropical cyclones with extreme surface winds **increased** in number while weaker storms decreased.
- Knutson et al. (2010): future projections based on theory and high-resolution dynamical models consistently indicate that greenhouse warming will cause the globally averaged intensity of tropical cyclones to shift towards **stronger** storms, with intensity increases of 2–11% by 2100. Existing modelling studies also consistently project **decreases** in the globally averaged frequency of tropical cyclones, by 6–34%.
- Sugi and Yoshimura (2012): **Decreasing** trend of tropical cyclone frequency in 228-year (1872-2099) 60 km resolution AGCM simulation - due to the decrease of the upward mass flux in tropical cyclone formation regions, because of the rate of increase of dry static stability.
- Emanuel (2013) Downscaling CMIP5 climate models show **increased** tropical cyclone activity in the 21st century.



$$\underset{①}{\frac{\Delta\omega}{\omega}} \approx \underset{②}{\frac{\Delta p}{p}} - \underset{③}{\frac{\Delta s}{s}}$$

① Upward mass flux change

② Precipitation change

③ Static stability change

1880 2080

Sugi and Yoshimura (2012)

Motivation

- Under the Global Warming Scenario,
  - the atmosphere - more stable
  - the monsoon/Hadley circulation - weaker
  - the number of global TCs - less
  - the number of intense TCs - more
- Questions?

  1. Is the atmosphere getting more stable?

  2. Why does the total number of TCs decrease?

  3. Why does the number of intense TCs increase?

As a first step to answer the 1st/2nd questions, we check the reanalysis data to examine the trend of the deep convective activity and atmospheric instability using the Arakawa-Schubert cumulus cloud ensemble diagnostics.

What I did

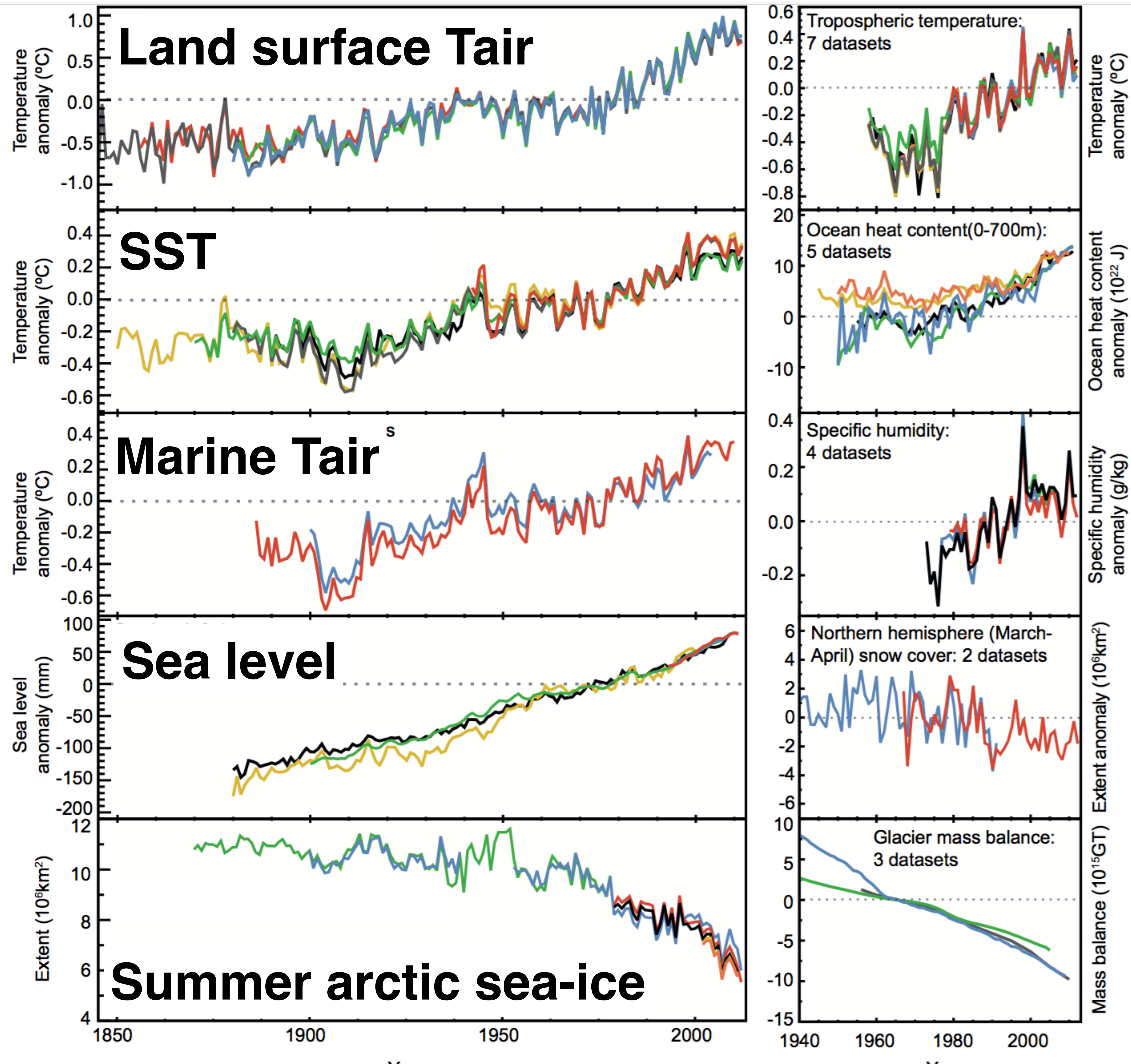
- Using the monthly reanalysis data from 1900 to 2010
- Applied the Arakawa-Schubert cumulus convective ensemble diagnostic to get the fractional entrainment rate λ for each convective cloud from the moist static energy profile
- Computed the highest convective cloud top level (CTL) under the environmental parameters, T and q, by using the zero-buoyancy condition at the CTL
- Calculated the temporal change of the 30-year mean of the CTL each calendar month

to show if the atmosphere has been getting more **stable** or **unstable** in the 20th century.

ERA-20C

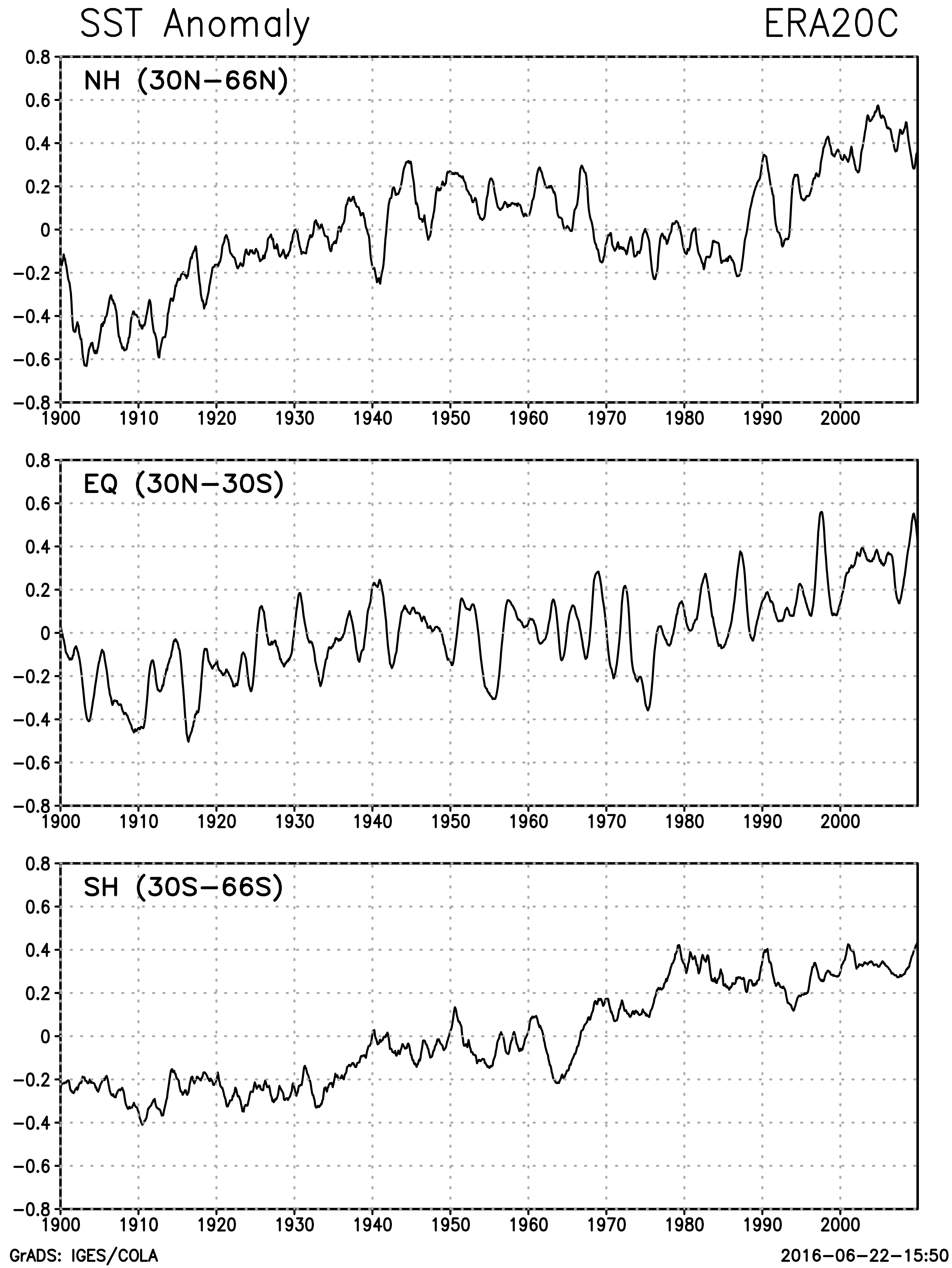
- ERA-20C is ECMWF's first atmospheric reanalysis of the 20th century, from 1900-2010.
- It assimilates observations of surface pressure and surface marine winds only. It is an outcome of the ERA-CLIM project.
- A coupled Atmosphere/Land-surface/Ocean-waves model is used to reanalyze the weather, by assimilating surface observations.
- The horizontal resolution is approximately 125 km (spectral truncation T159). Note, atmospheric data are not only available on the native 91 model levels, but also on 37 pressure levels (as in ERA-Interim), 16 potential temperature levels, and the 2 PVU potential vorticity level.
- Daily, invariant, and monthly mean data are available from the ERA-20C ECMWF Public Datasets web interface.

(http://www.ecmwf.int/en/research/climate-reanalysis/era-20c)



Land surface Tair
SST
Marine Tair
Sea level
Summer arctic sea-ice
Temperature anomaly (°C)
Sea level anomaly (mm)
Extent (10⁶km²)
Tropospheric temperature: 7 datasets
Ocean heat content(0-700m): 5 datasets
Ocean heat content anomaly (10²² J)
Specific humidity: 4 datasets
Specific humidity anomaly (g/kg)
Northern hemisphere (March-April) snow cover: 2 datasets
Extent anomaly (10⁶km²)
Glacier mass balance: 3 datasets
Mass balance (10¹⁵GT)

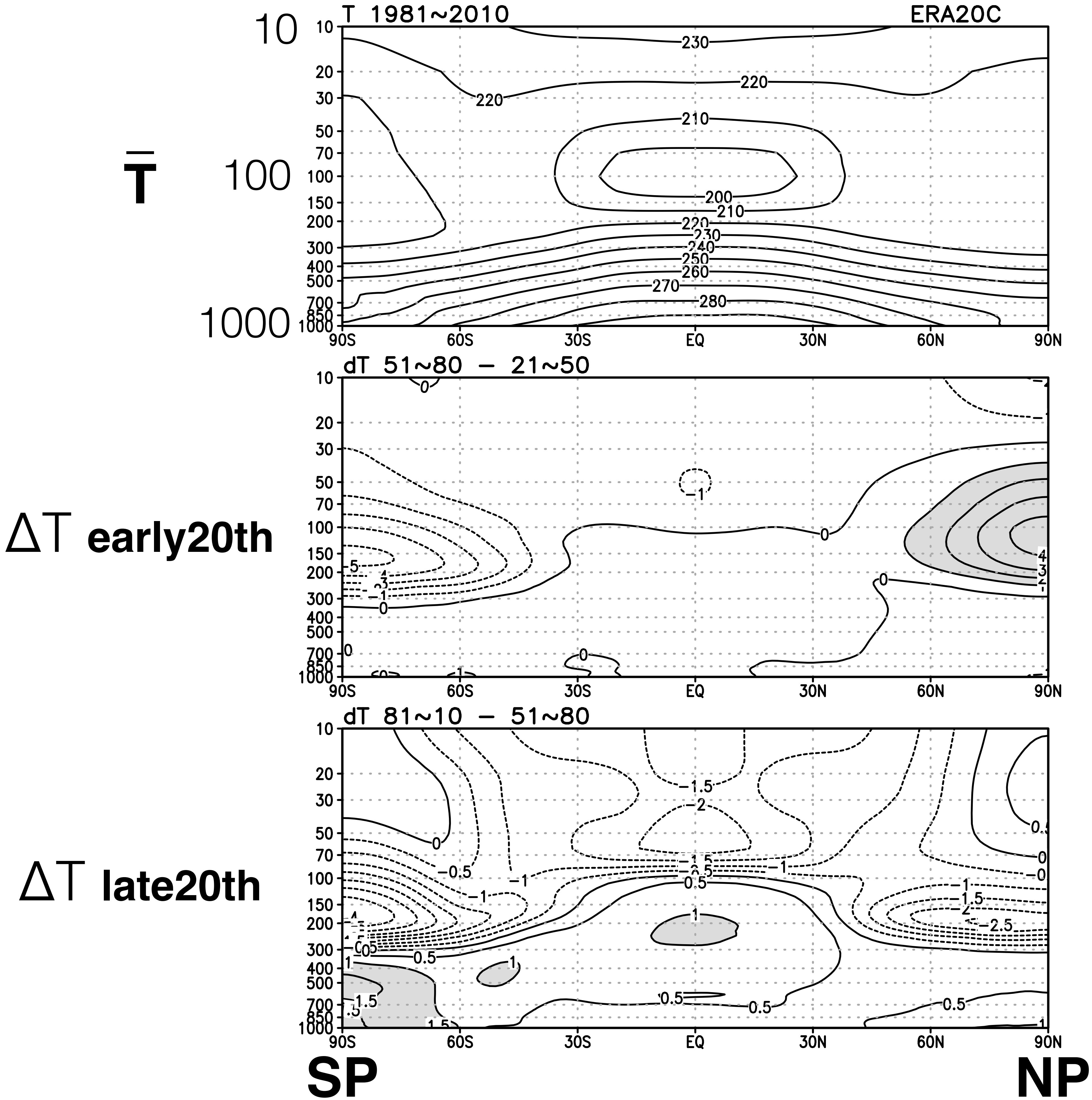
SSTA


SST Anomaly
ERA20C
NH (30N–66N)
EQ (30N–30S)
SH (30S–66S)
0.8
0.6
0.4
0.2
0
–0.2
–0.4
–0.6
–0.8
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
GrADS: IGES/COLA
2016-06-22-15:50

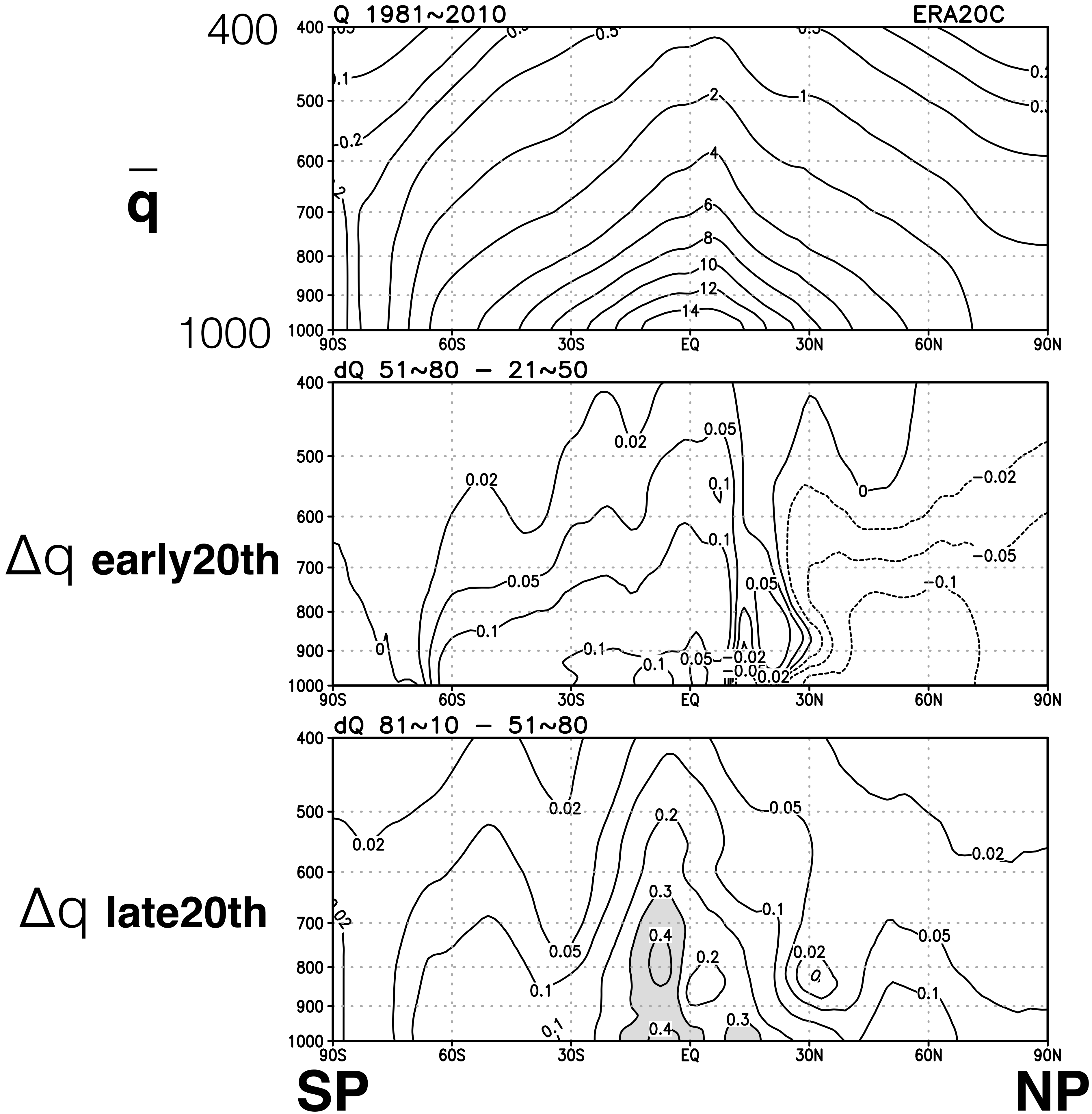
NH

TR

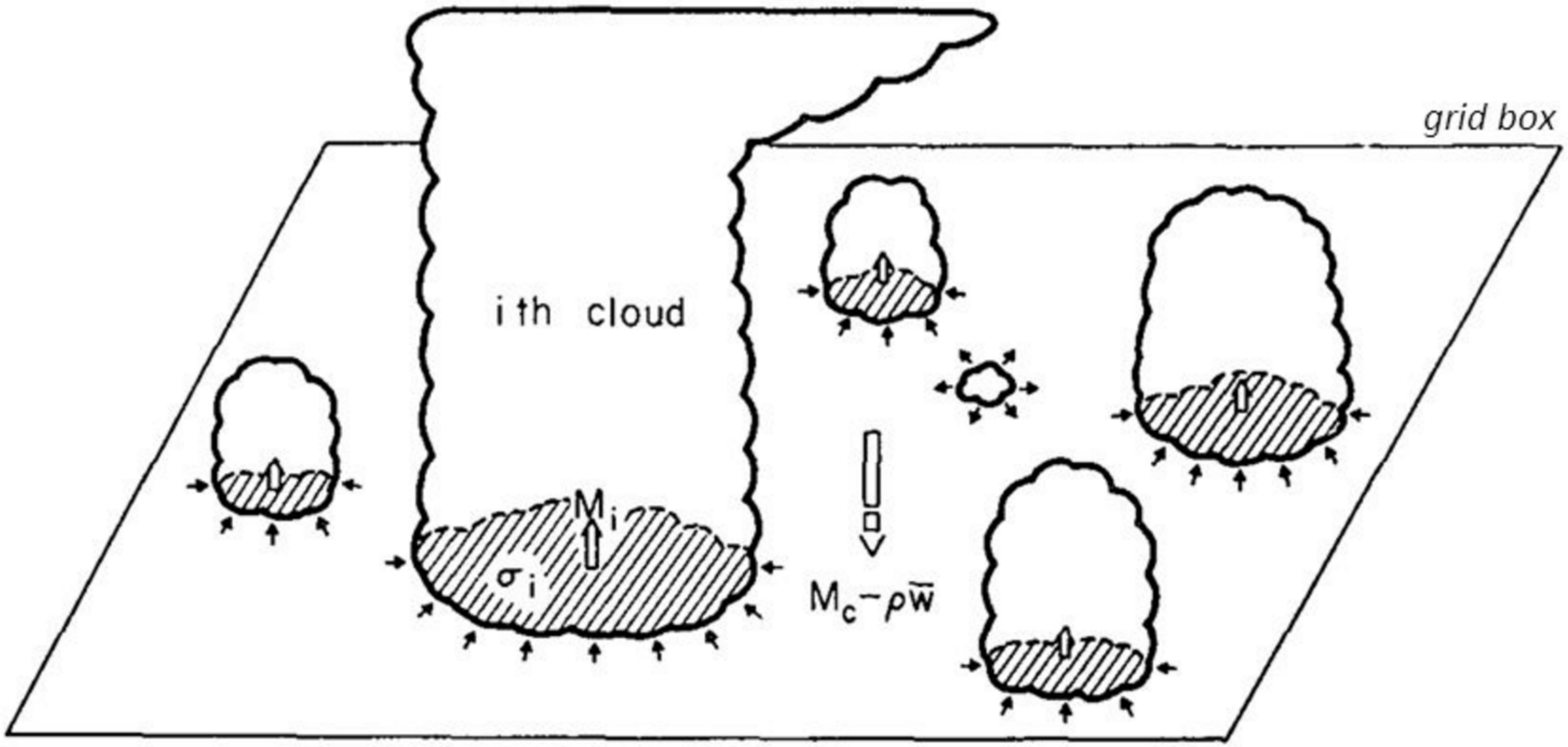
SH



T 1981~2010
ERA20C
T̄
10
100
1000
dT 51~80 − 21~50
ΔT early20th
dT 81~10 − 51~80
ΔT late20th
90S
60S
30S
EQ
30N
60N
90N
SP
NP

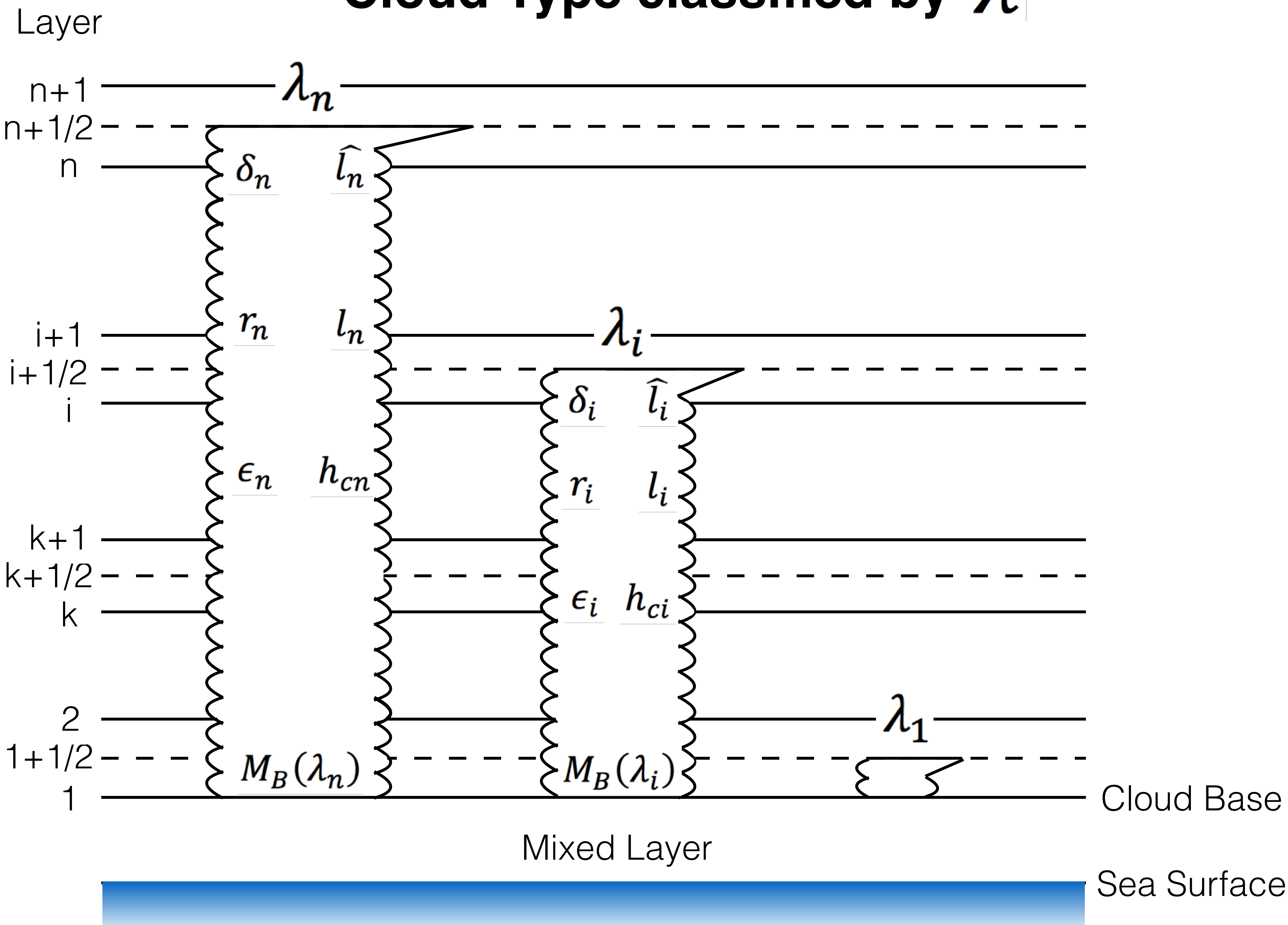

400
1000
q̄
Δq early20th
Δq late20th
Q 1981~2010
ERA20C
dQ 51~80 − 21~50
dQ 81~10 − 51~80
90S
60S
30S
EQ
30N
60N
90N
SP
NP

Arakawa and Schubert (1974)



- **Cumulus Parameterization Scheme**
  - for sub-grid scale cumulus effect in the coarse GCM
- **Diagnostic Study of Cumulus Ensemble**
  - for heat/moisture budget (Q1, Q2), cloud mass flux, cumulus population

Cloud Type classified by λ



Modified Fig. 2 of Nitta(1975)

Moist Static Energy h

$$h = C_p T + gz + Lq$$
$$h^* = C_p T + gz + Lq^*$$

Specific Enthalpy	Potential Energy	Latent Energy

Cp: specific heat of air under constant pressure (1.0057 $Jkg^{-1}K^{-1}$)
T: temperature (K)
g: gravity (9.8 $Jkg^{-1}m^{-1}$)
z: geopotential per unit mass (m)
L: latent heat per unit mass of water vapor (2260 Jkg^{-1})
q: mixing ratio (kg/kg), q*: saturated mixing ratio

Cloud Top Height Condition

$$\widehat{h_{ci}} = \overline{h^*} - \Delta h\left(\overline{q^*}, \bar{q}, \hat{l}\right)$$

h of the i-th cloud type at the detrainment level

Virtual Temperature Correction

(Arakawa & Shubert, 1974)

Cloud Base Condition

$$h_m = C_p T_B + g z_B + L q_m$$

where,

$$T_B = 0.5 * (\theta(975) + \theta(1000) \times (\frac{950}{1000})^{R/Cp}$$

$$z_B = 950\ hPa$$

$$q_m = 0.5 * \left(\bar{q}\ (975) + \bar{q}(1000)\right)$$

(Lord, 1982)

How to calculate λ

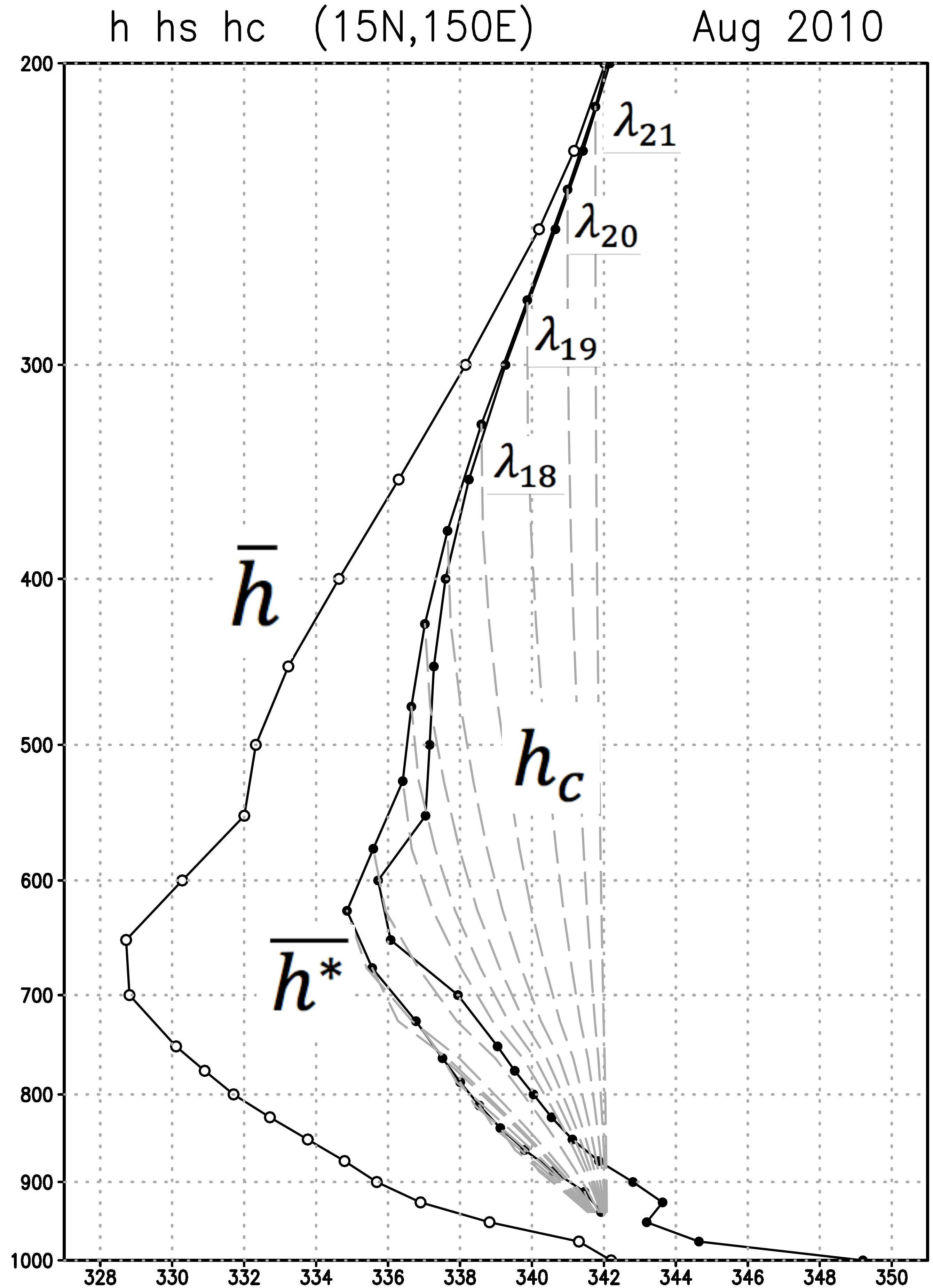
$$\frac{\partial \eta}{\partial z} = \lambda \eta \;\rightarrow\; \frac{\eta_{k+\frac{1}{2}} - \eta_{k-\frac{1}{2}}}{\Delta z_k} = \lambda_i \eta_{k+\frac{1}{2}} \rightarrow\; \eta_{k+\frac{1}{2}} = \eta_{k-\frac{1}{2}}(1 + \lambda_i \Delta z_k)$$

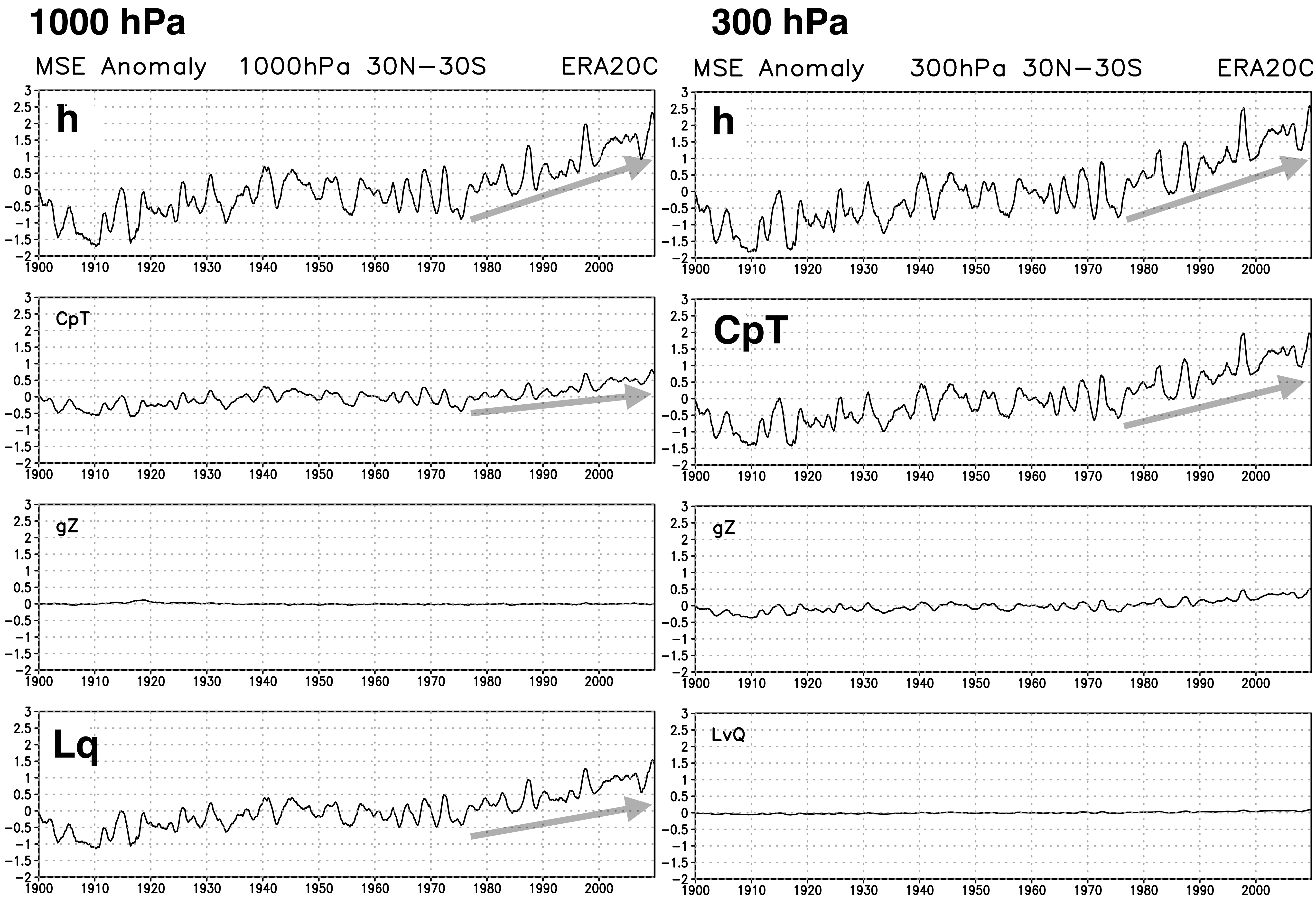
$$\frac{\partial \eta h_c}{\partial z} = \lambda \eta \bar{h} \;\rightarrow\; \frac{\eta_{k+\frac{1}{2}} h_{c_{k+\frac{1}{2}}} - \eta_{k-\frac{1}{2}} h_{c_{k-\frac{1}{2}}}}{\Delta z_k} = \lambda_i \eta_{k+\frac{1}{2}} \bar{h}_k \rightarrow h_{ck+\frac{1}{2}} = \frac{h_{c_{k-\frac{1}{2}}} + \lambda_i \Delta z_k \overline{h_k}}{1 + \lambda_i \Delta z_k}$$

$$\mathcal{F}[\lambda_i] \equiv \widehat{h_{ci}} - \overline{h^*} = 0$$

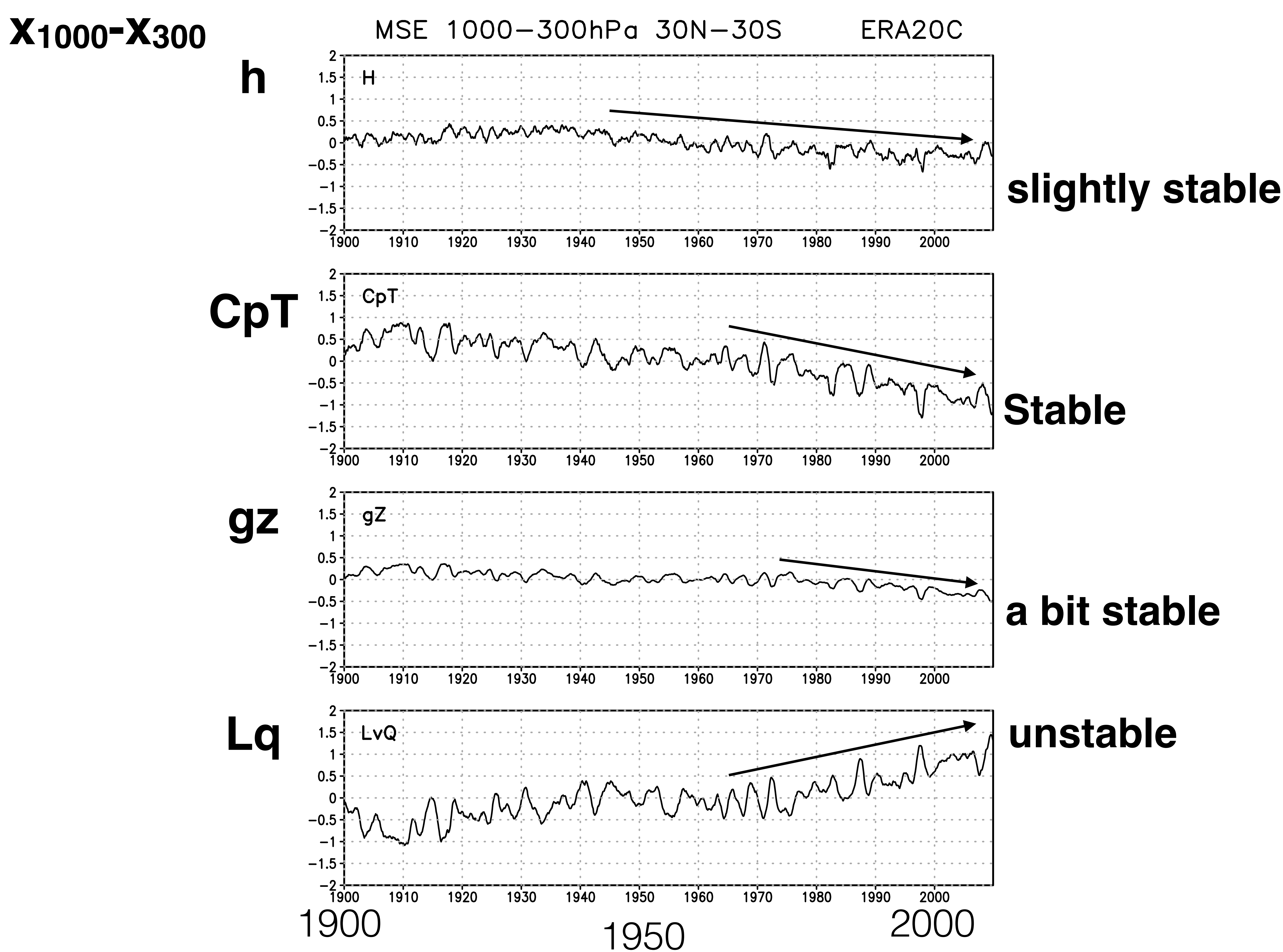
λ_i can be solved iteratively by the method of false position (Gerald, 1970)

Vertical Profile of h





1000 hPa
300 hPa
MSE Anomaly 1000hPa 30N–30S ERA20C
MSE Anomaly 300hPa 30N–30S ERA20C
h
CpT
gZ
Lq
LvQ

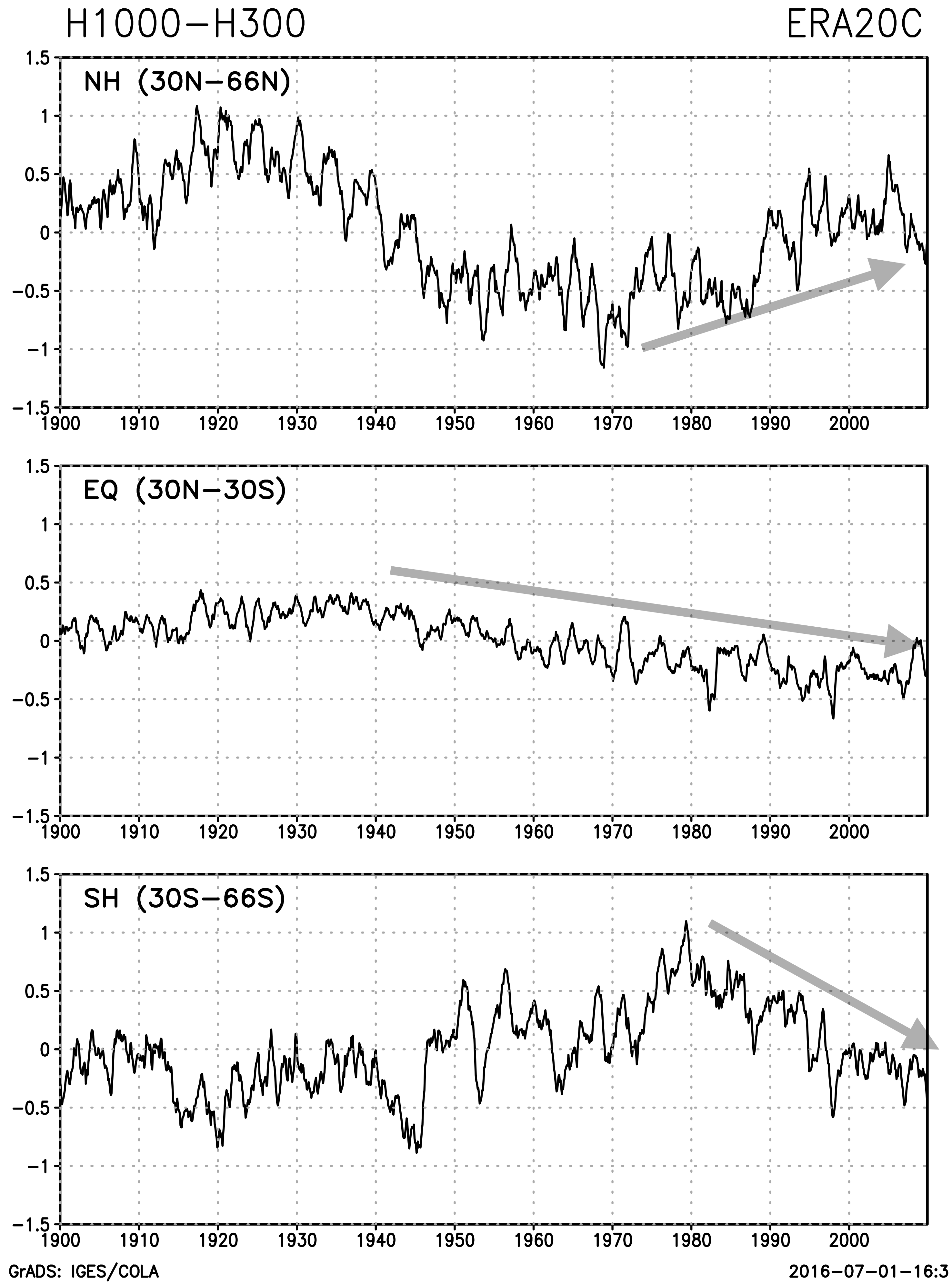

x1000-x300
MSE 1000-300hPa 30N-30S ERA20C
h
H
slightly stable
CpT
CpT
Stable
gz
gZ
a bit stable
Lq
LvQ
unstable
1900
1950
2000

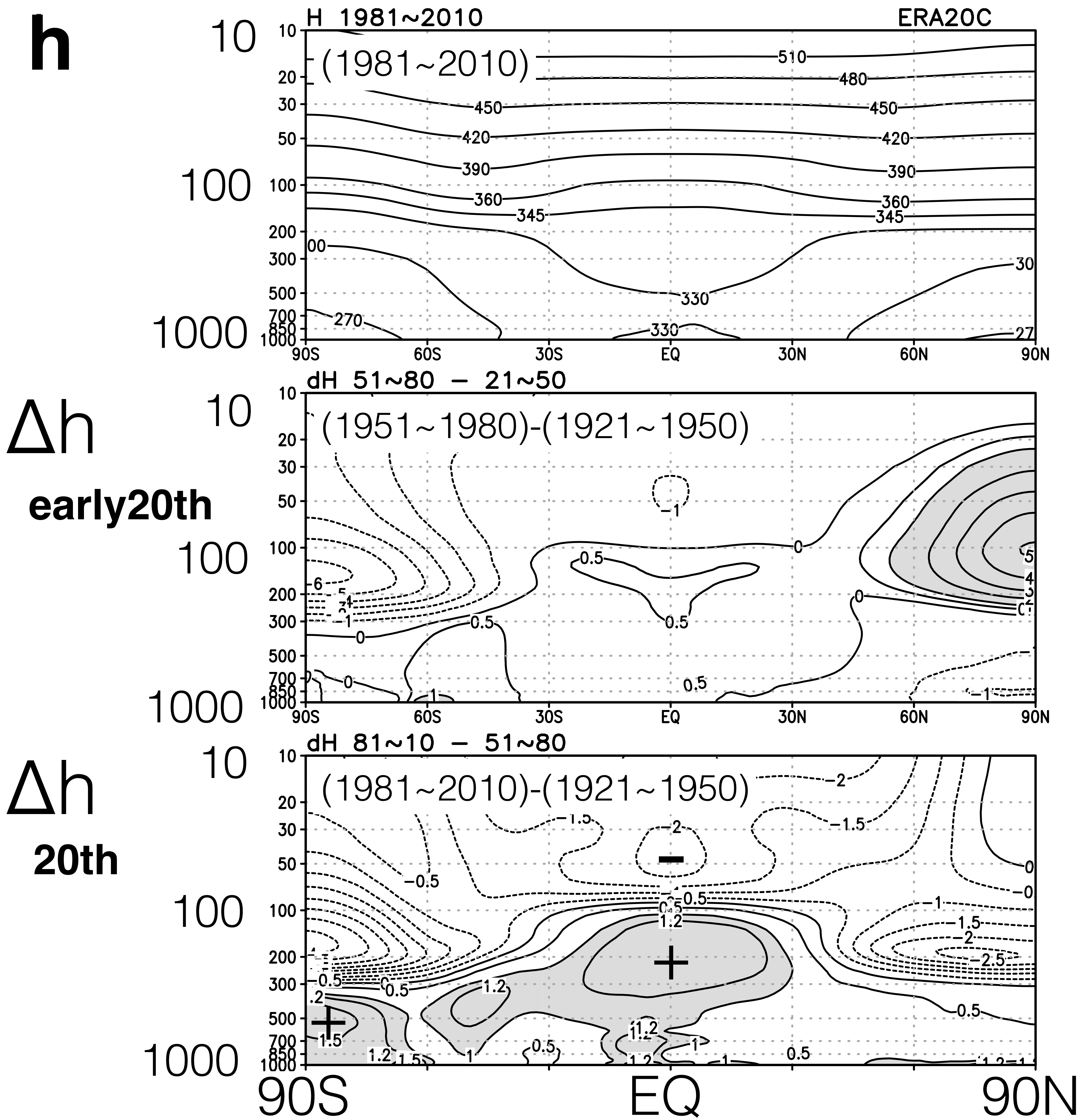
h_{1000}-h_{300}

NH

TR

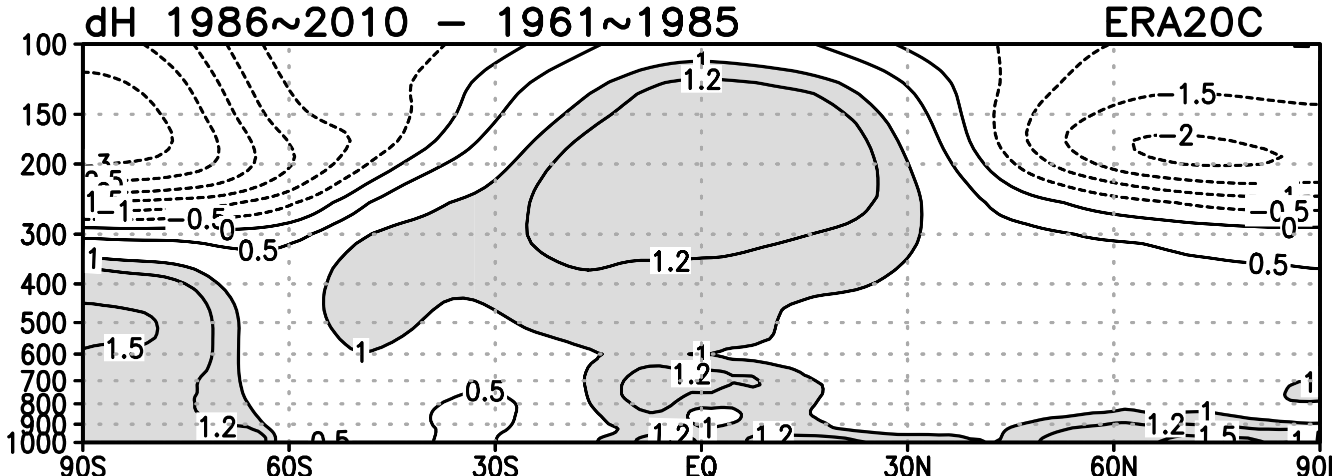
SH



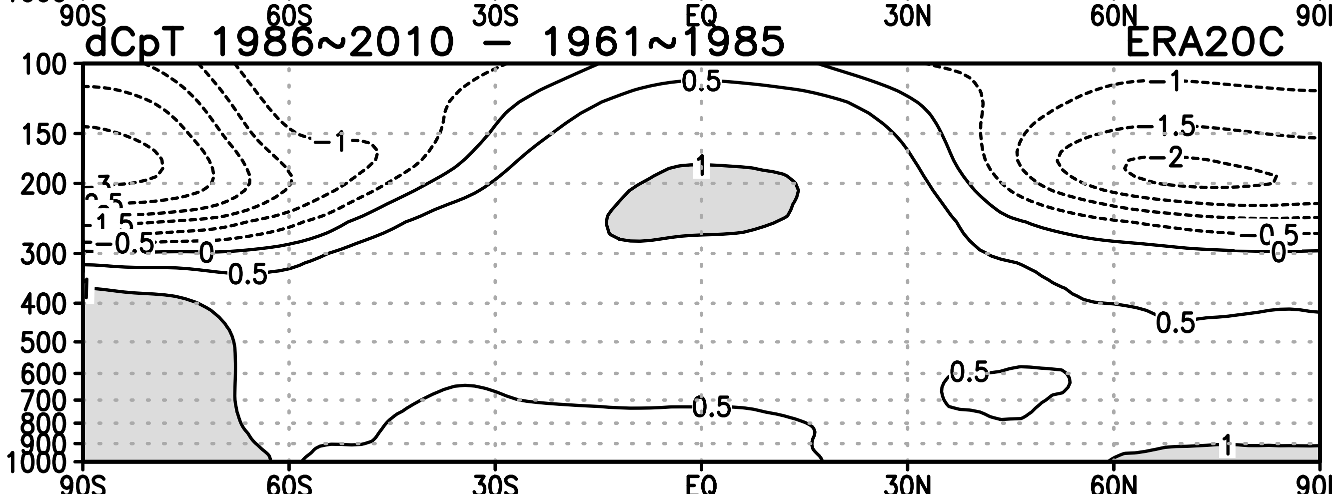


h
H 1981~2010
ERA20C
(1981~2010)
Δh
early20th
dH 51~80 − 21~50
(1951~1980)-(1921~1950)
Δh
20th
dH 81~10 − 51~80
(1981~2010)-(1921~1950)
90S
EQ
90N

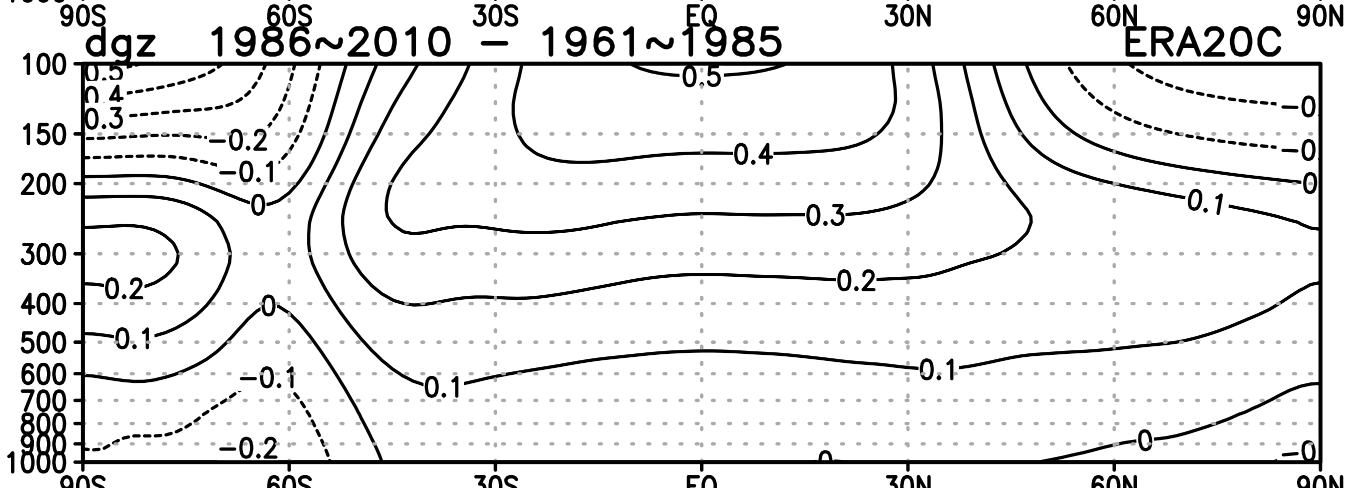
dh/dt



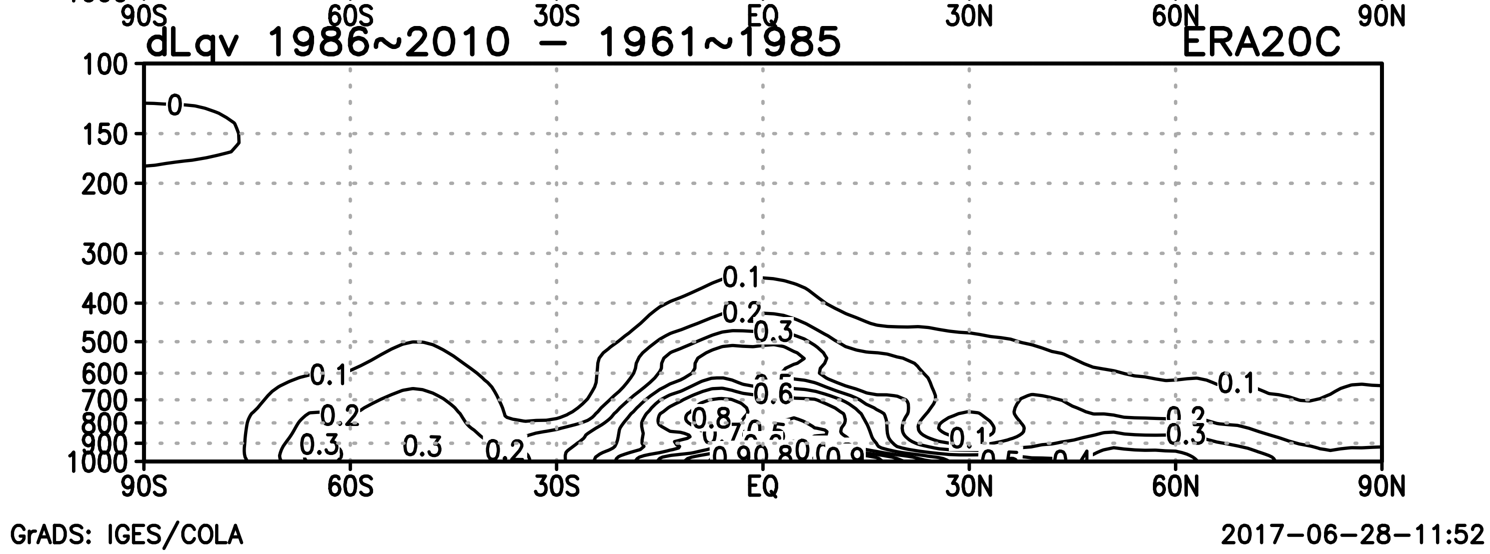
CpdT/dt



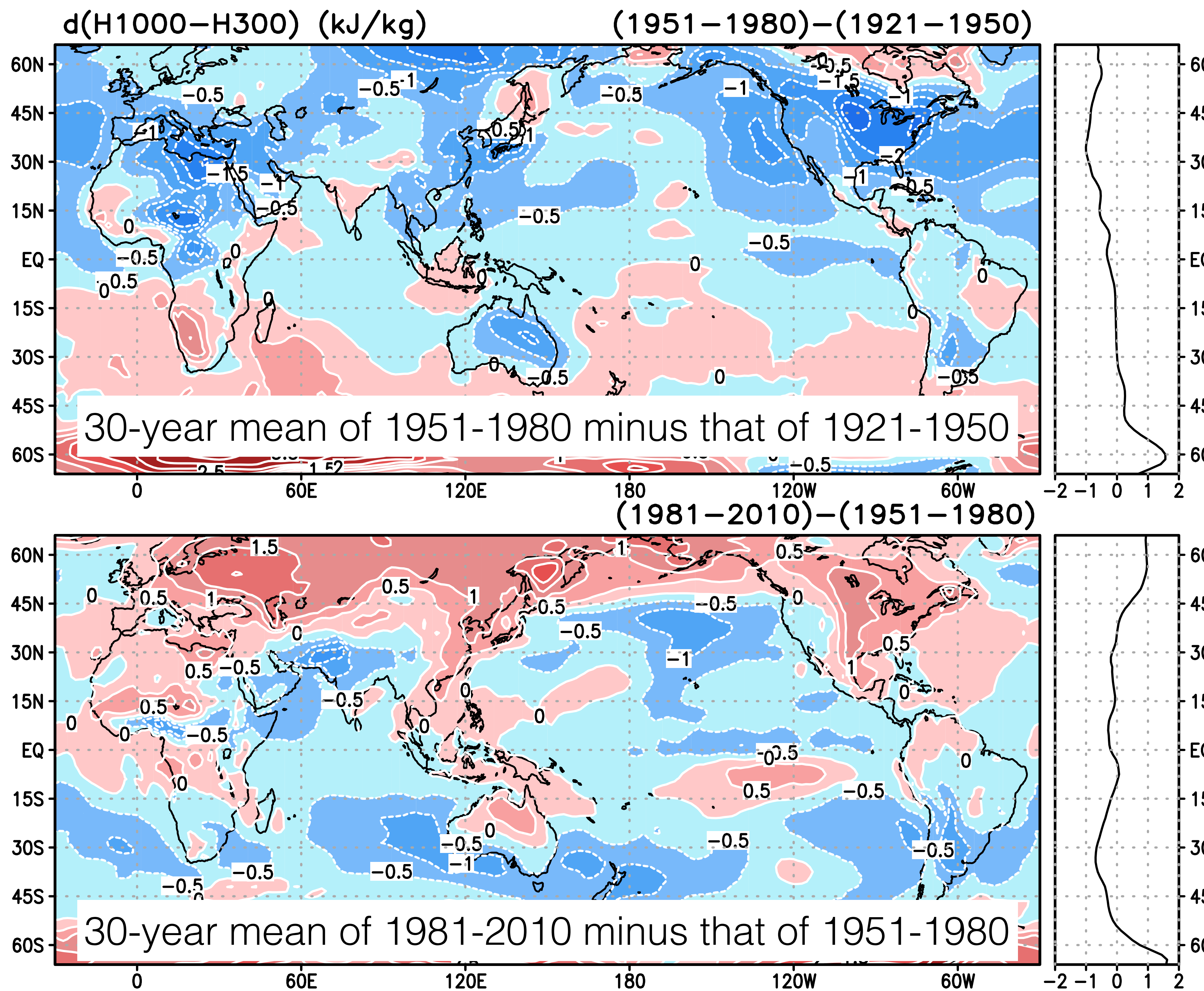
gdz/dt



Ldq/dt



$d(h_{1000}-h_{300})/dt$

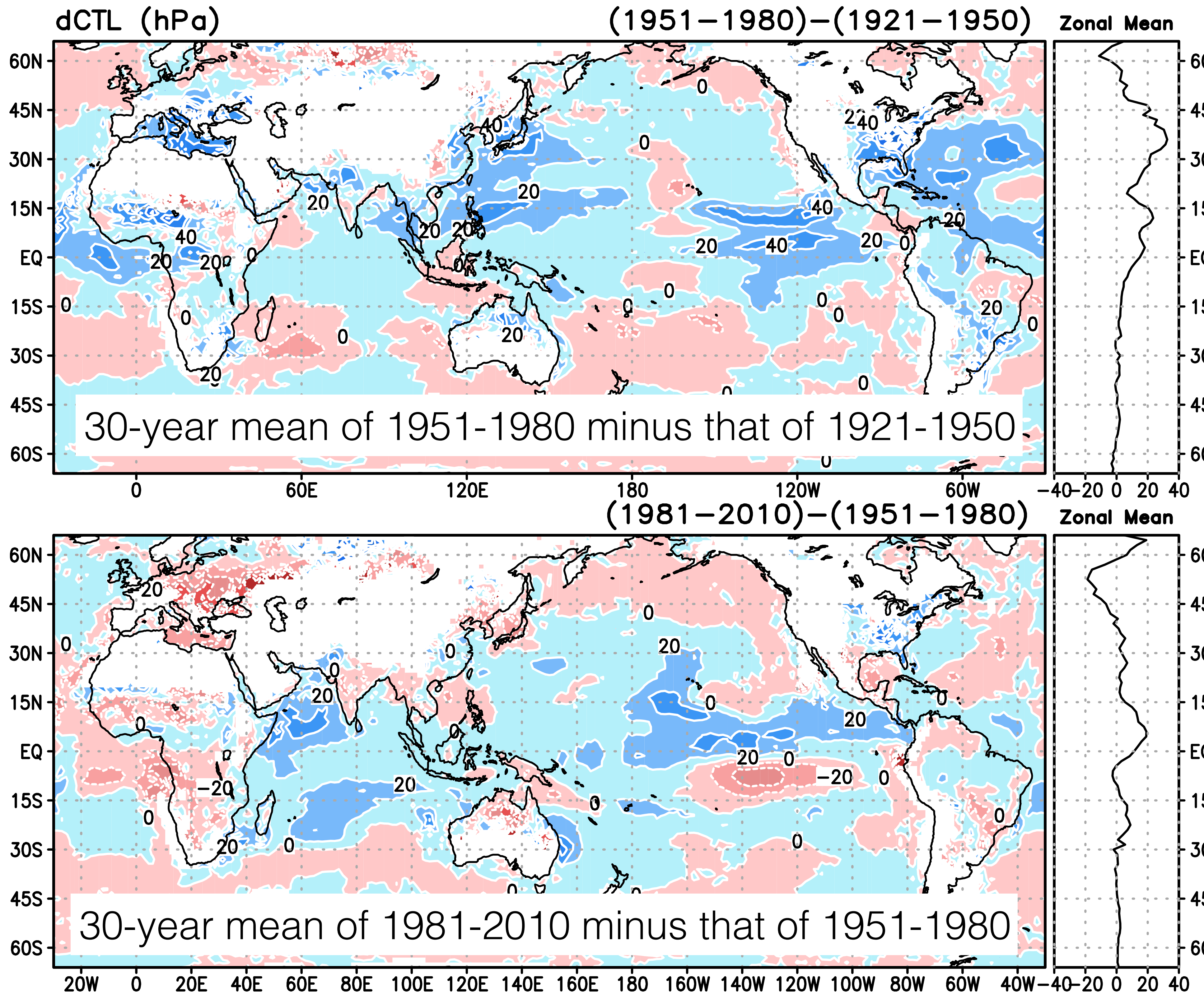


GrADS/COLA

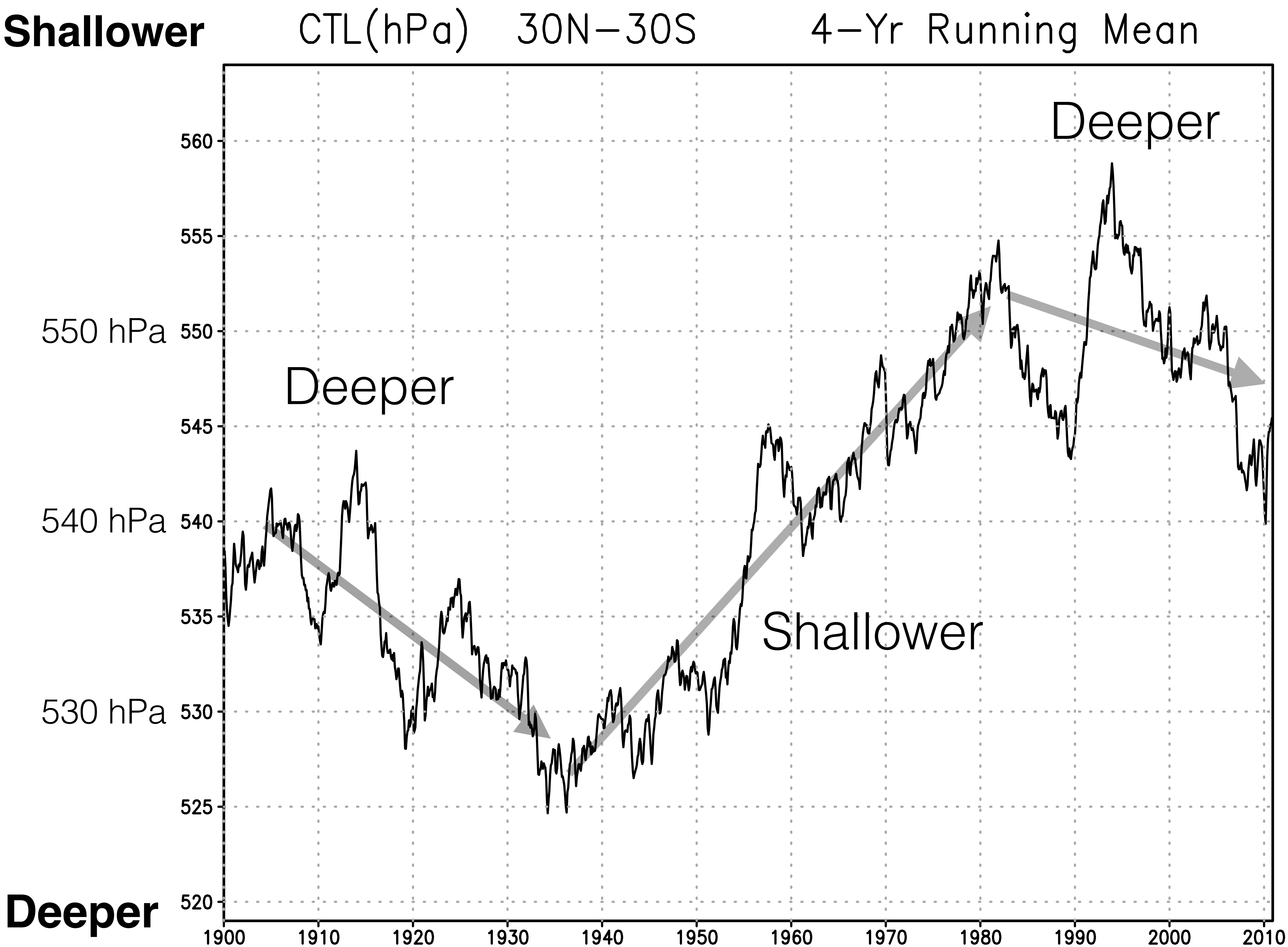
2018−12−03−10:10

Negative - blue (getting more stable)

d(CTL)/dt



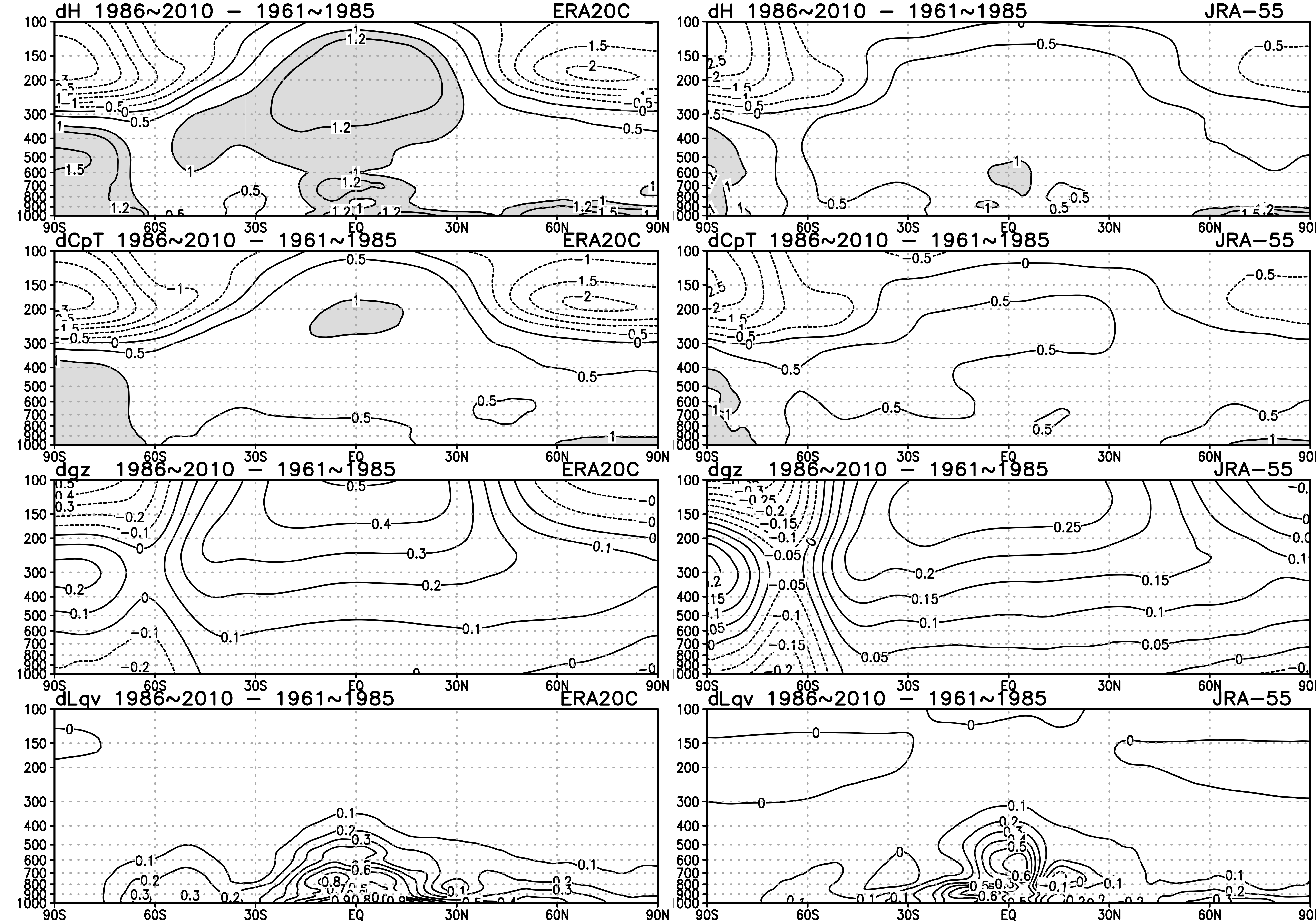
Positive - blue (weaker convection)



Shallower
CTL(hPa) 30N-30S 4-Yr Running Mean
Deeper
550 hPa
540 hPa
530 hPa
Deeper
Shallower
Deeper
560
555
550
545
540
535
530
525
520
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

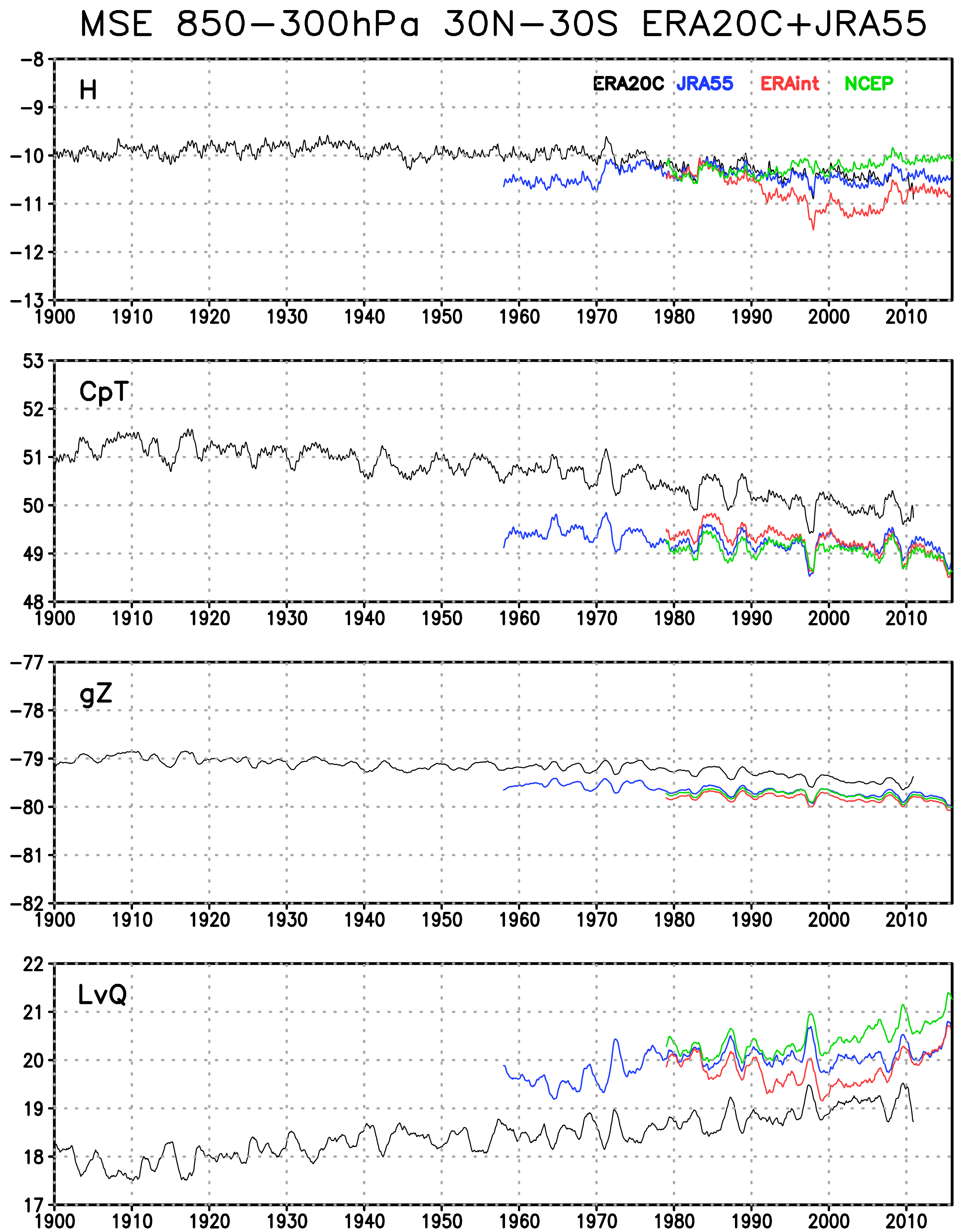
Other Reanalysis Dataset?

ERA20C **JRA55**



$d(h_{1000}-h_{300})/dt$

with different datasets



ERA20C : bias from others
CpT - larger
LvQ - smaller
Limit of DA?

Temporal Changes
Similar but different

Verification

1981-2010

OLR

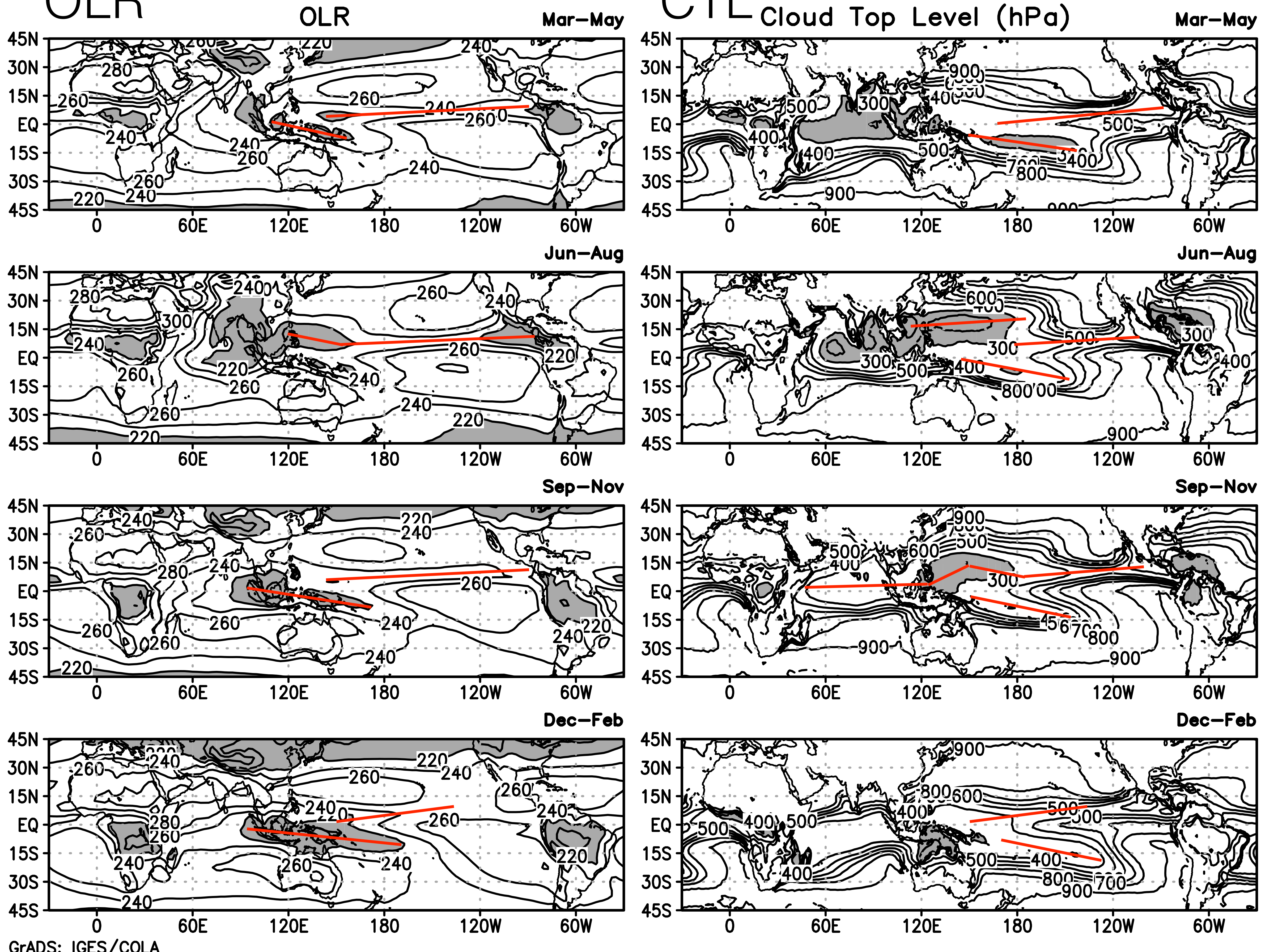
CTL

S

S

F

W



1981-2010

OLR

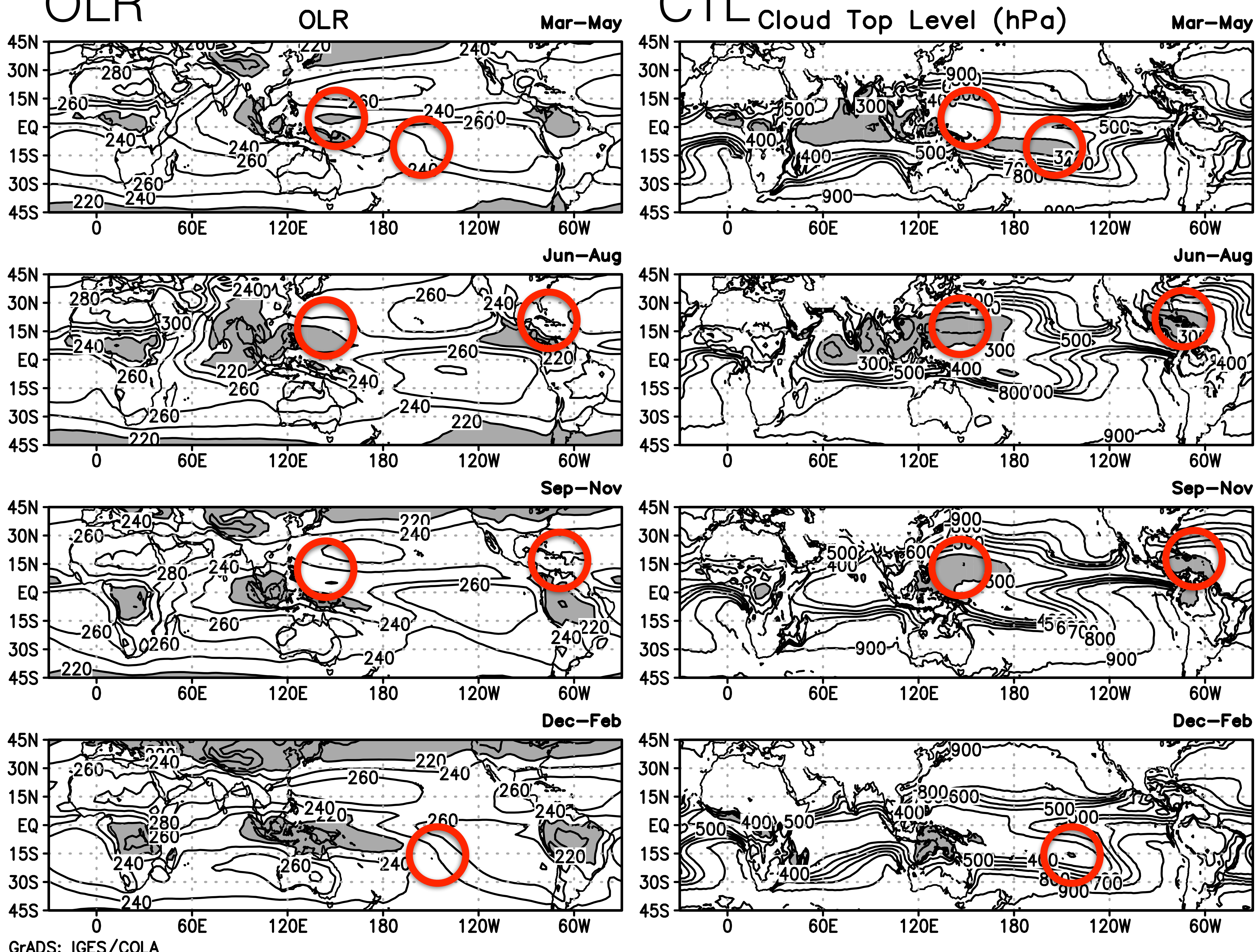
CTL

S

S

F

W



Conclusion

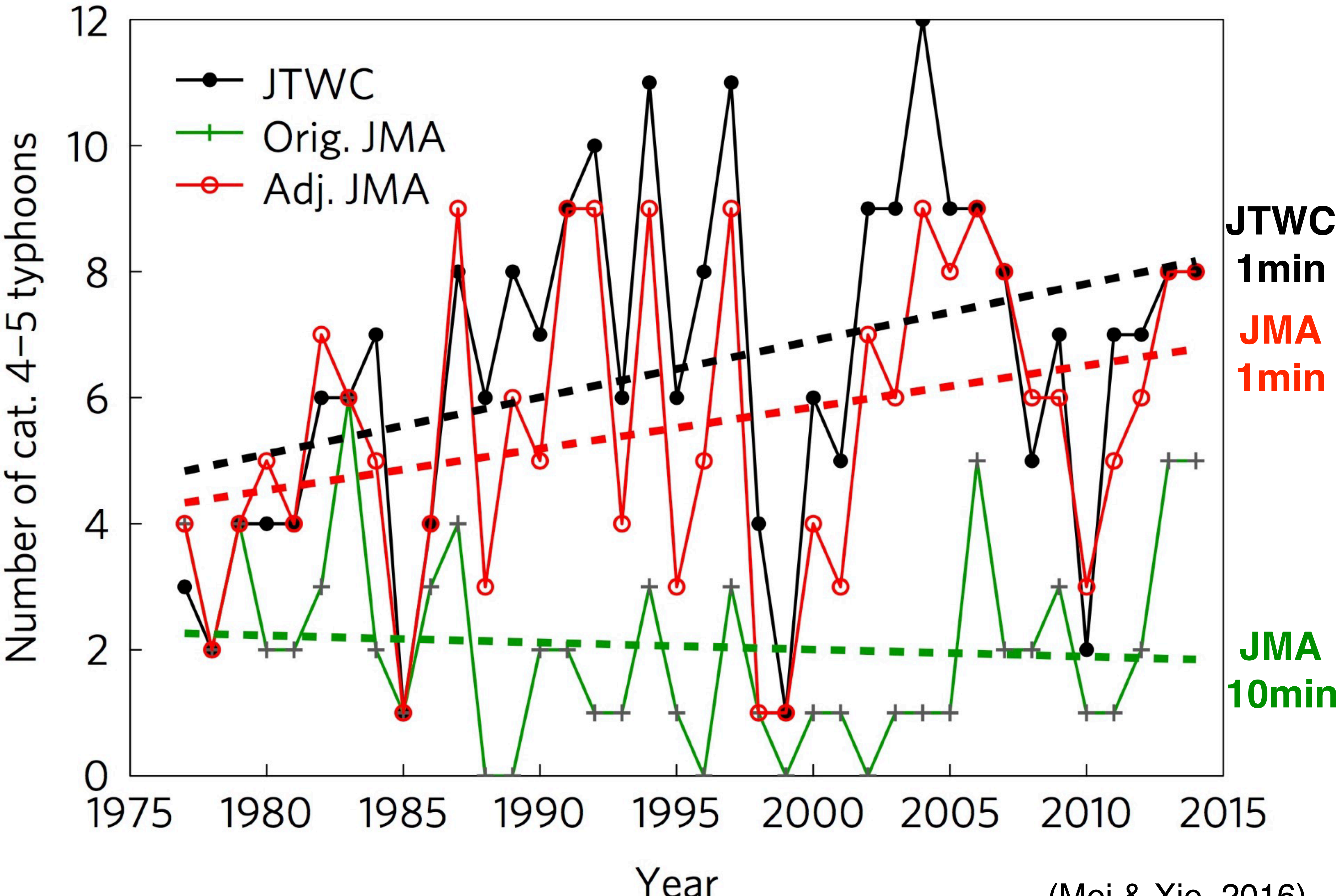
- The monthly evolution of the convective activity in the 20th century over the globe has been examined using the ECMWF 20 Century reanalysis data (ERA-20C).

- Based on the Arakawa-Schubert convective cloud ensemble diagnostics, convective cloud types at each grid point from 1900 to 2010 are computed.

- **The detrainment level of the deepest cloud type, cloud top height, shows lower trend in time**, indicating that the convective activity is getting weaker, mainly due to the weaker atmospheric instability, which is the same conclusion Sugi and Yoshimura (2012) suggests.

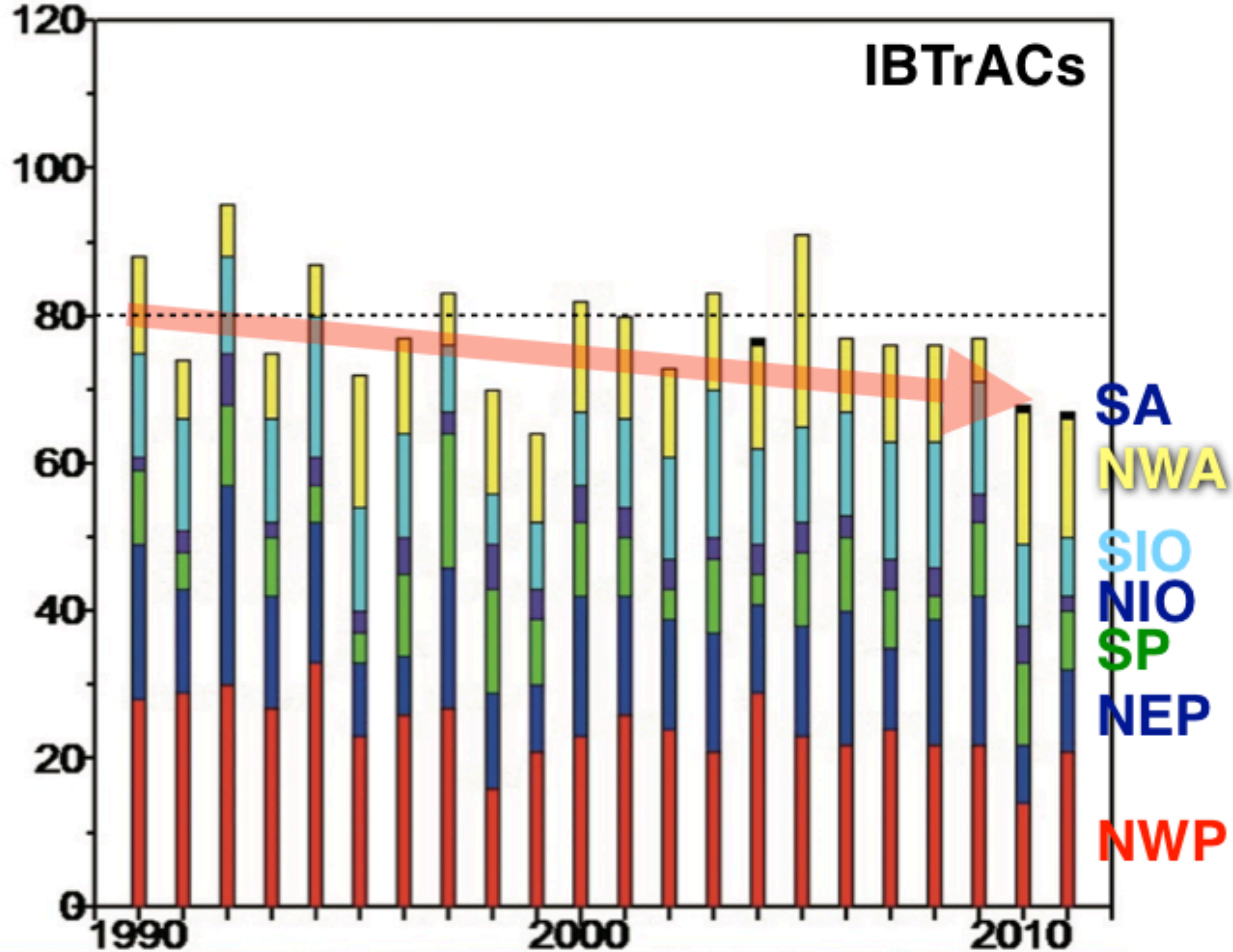
Any signature in the available data?

Are intense typhoons increasing or decreasing?



(Mei & Xie, 2016)

Global TC numbers in the past almost flat or decreasing?



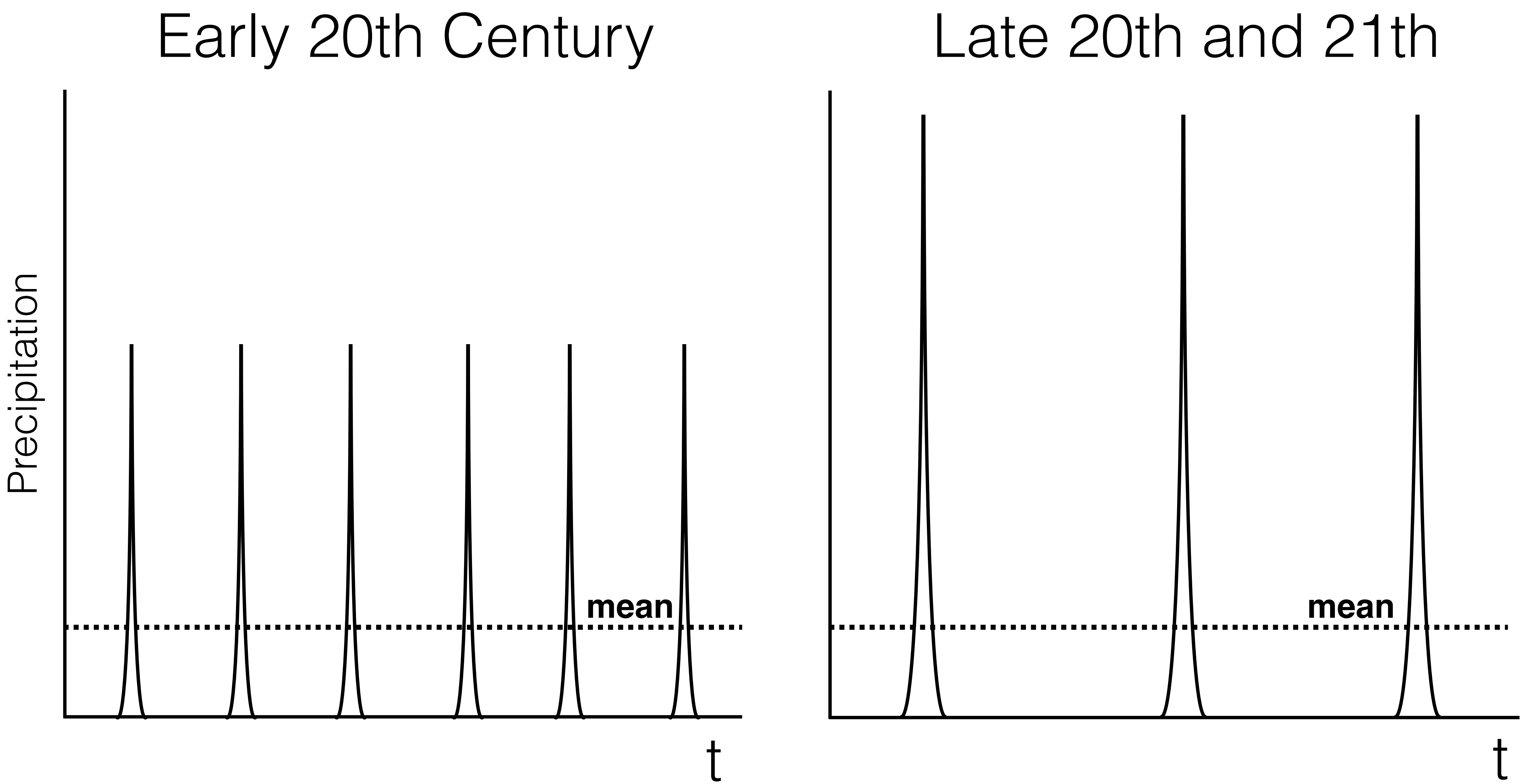
(Fudeyasu et al., 2014)

Next Steps

- To answer the third question, “Why does the number of intense TCs increase?”, it would be required to use the sub-daily data to compute the climatological probabilistic density function of the “cloud top level (CTL)”. It is anticipated that there would be more chance to have higher CTLs, but the climatological mean CTL will be lower in late 20th century.

- Cloud mass flux will also be computed to confirm the consistency of the result. That is, the climatological cloud mass flux would be getting weaker, as the cloud top level is lower, but individual one associated with TC will be stronger in late 20th century.

More severe rains, but less frequent



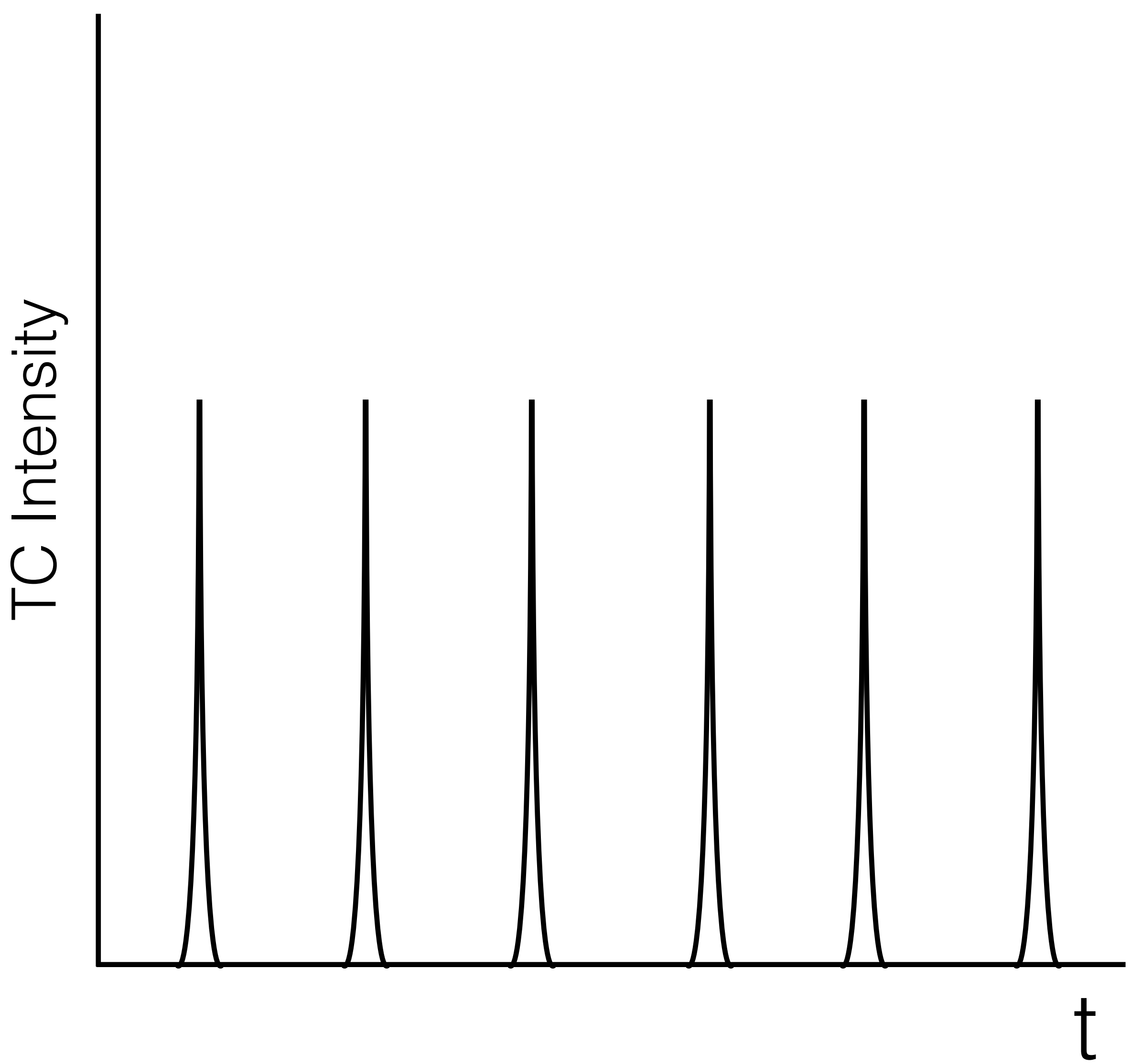
Less frequency = More stable atmosphere

More severity = More warmer/humid near the surface

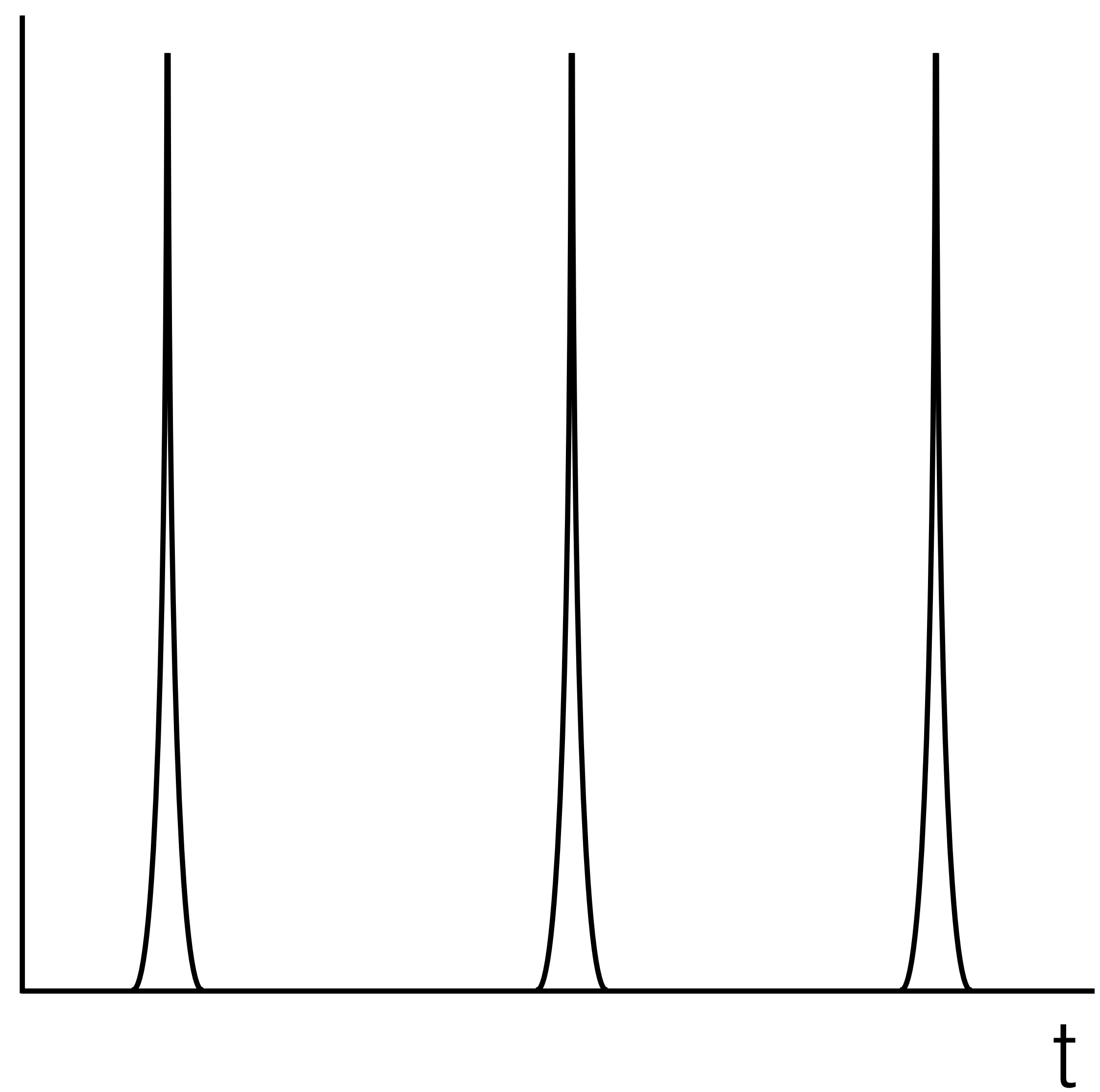
Mean value doesn't tell much!

More severe TCs, but less frequent

Early 20th Century



Late 20th and 21th



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