The co-variations of tropical temperature and humidity across multiple timescales and their implication on the estimation of surface radiation budget

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1. At a fixed location in tropical troposphere, make high-frequency measurements, what would be the sign of the correlation coefficient of $\langle T(t|x,y,p), q(t|x,y,p)\rangle$? Why?
2. If average is done over a period, say, one month, what would be $\langle T(\bar{t}|x,y,p), q(\bar{t}|x,y,p)\rangle$? Same as the answer to #1 or not?
3. If average is done over a period and a geographical region, say, the entire tropics, what would be $\langle T(\bar{t},\bar{x},\bar{y}|p), q(\bar{t},\bar{x},\bar{y}|p)\rangle$? Why?
4. If we look at interannual anomalies correlation $\langle T_a(\bar{t},\bar{x},\bar{y}|p), q_a(\bar{t},\bar{x},\bar{y}|p)\rangle$, will it differ from the results in #3? Why?
5. Which of above relations matter most for the climate change simulation and projection?

Over a time and regional average: constant RH hypothesis

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Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity

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(Manuscript received 2 November 1966)

1. Introduction

This study is a continuation of the previous study of the thermal equilibrium of the atmosphere with a convective adjustment which was published in the JOURNAL OF THE ATMOSPHERIC SCIENCES (Manabe and Strickler, 1964). Hereafter, we shall identify this study by M.S. In M.S. the vertical distribution of absolute humidity was given for the computation of equilibrium temperature, and its dependence upon atmospheric temperature was not taken into consideration. However, the absolute humidity in the actual atmosphere strongly depends upon temperature. Fig. 1 shows the distribution of relative humidity as a function of latitude and height for summer and winter. According to this figure, the zonal mean distributions of relative humidity of two seasons closely resemble one another, whereas those of absolute humidity do not. These data suggest that, given sufficient time, the atmosphere tends to restore a certain climatological distribution of relative humidity responding to the change of temperature. If the moisture content of the atmosphere depends upon atmospheric temperature, the effective height of the source of outgoing long-wave radiation also depends upon atmospheric temperature. Given a vertical distribution of relative humidity, the warmer the atmospheric temperature, the higher the effective source of outgoing radiation. Accordingly, the dependence of the outgoing long-wave radiation is less than that to be expected from the fourth-power law of Stefan-Boltzman. Therefore, the equilibrium temperature of the atmosphere with a fixed relative humidity depends more upon the solar constant or upon absorbers such as CO_2 and O_3, than does that with a fixed absolute humidity, in order to satisfy the condition of radiative convective equilibrium. In this study, we will repeat the computation of radiative convective equilibrium of the atmosphere, this time for an atmosphere with a given distribution of relative humidity instead of that for an atmosphere with a given distribution of absolute humidity as was carried out in M.S.

As we stated in M.S., and in the study by Manabe and Möller (1961), the primary objective of our study of radiative convective equilibrium is the incorporation of radiative transfer into the general circulation model

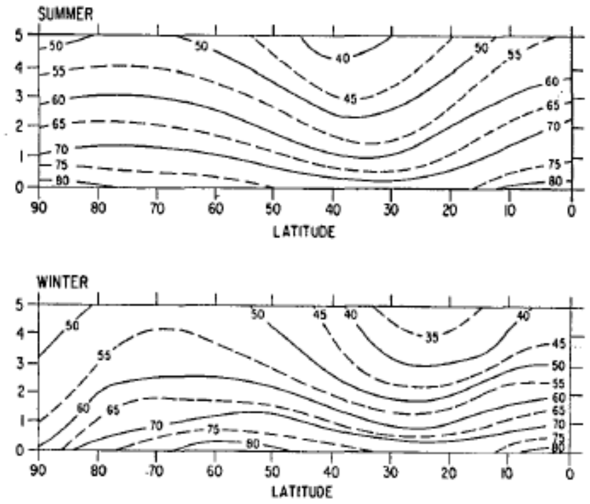
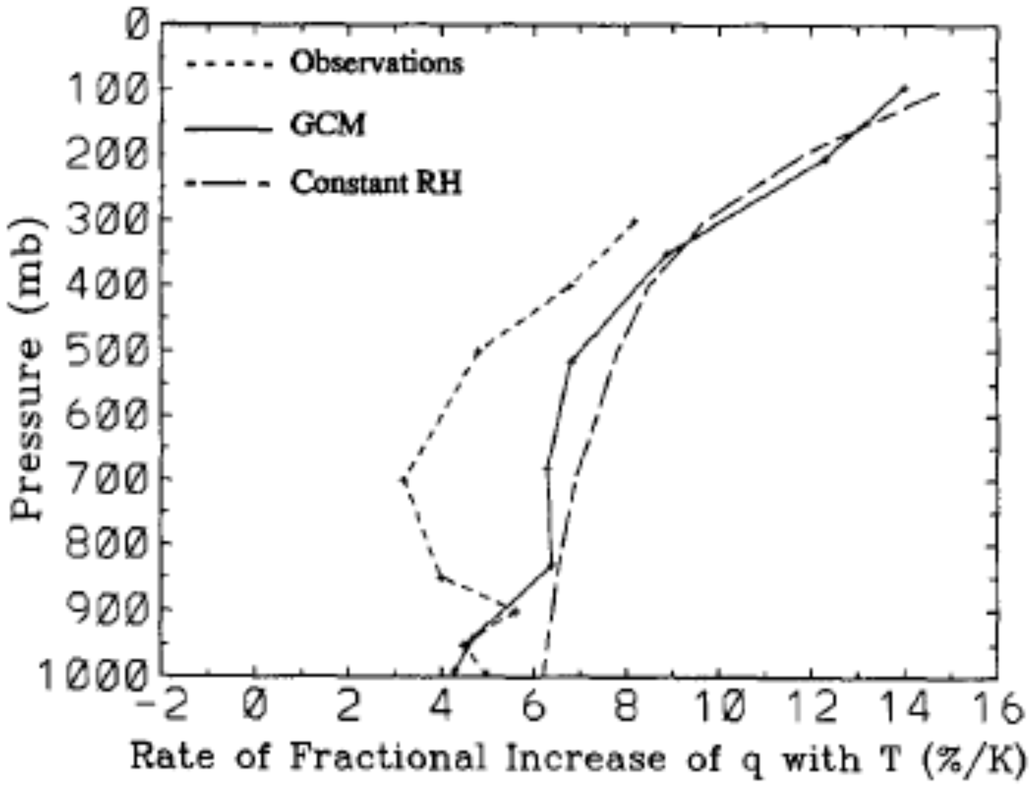


FIG. 1. Latitude-height distribution of relative humidity for both summer and winter (Telegadas and London, 1954).

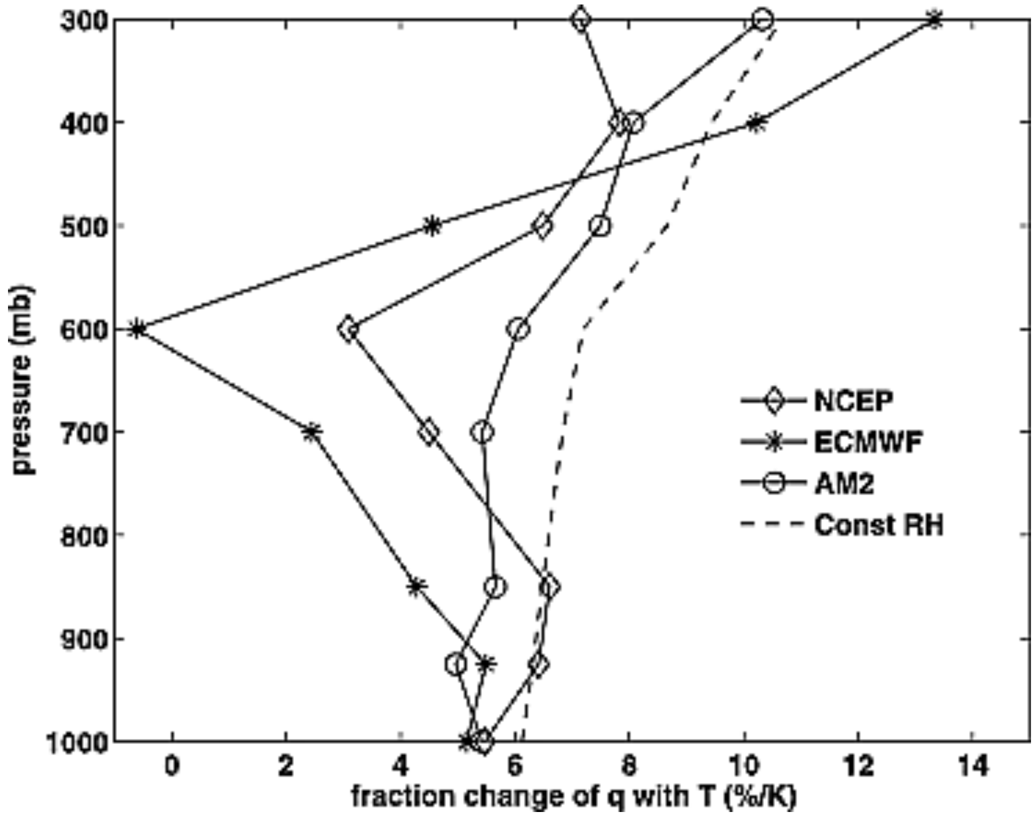
- If this constant RH hypothesis is approximately true, then <T, q> must be **strongly** positive

Interannual anomalies of tropical-mean T and q



(Sun & Held, 1996, J. Climate)

Obs: radiosonde
GCM: GFDL R15 model



NCEP-1
ERA-40

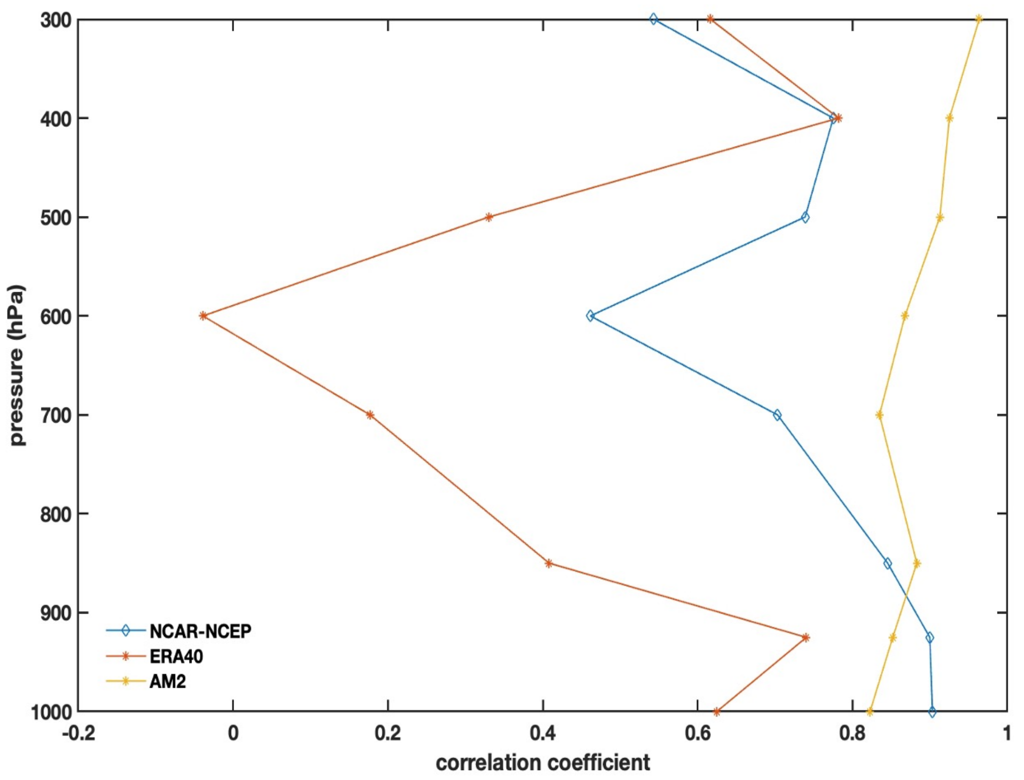
(Huang, Soden, and Jackson, GRL, 2005)

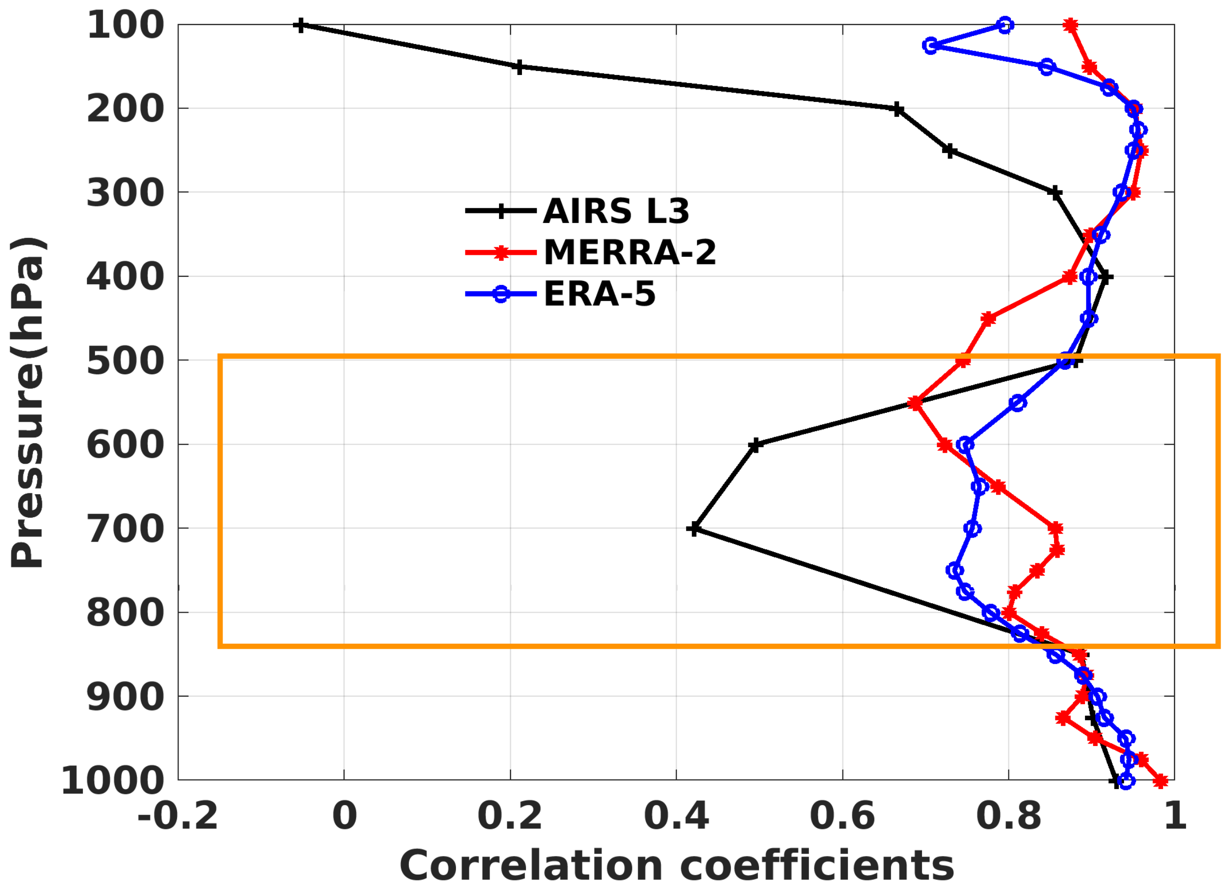
AM2: GFDL model for CMIP3 (AMIP run)
NCAR-NCEP/ERA40: 1st-generation reanalysis

Regression slope ∝ Cov(T_a, q_a)/var(T_a)

Constant RH: <T, q> = 1.0

Correlation coefficient of interannual anomalies of tropical-mean T and q



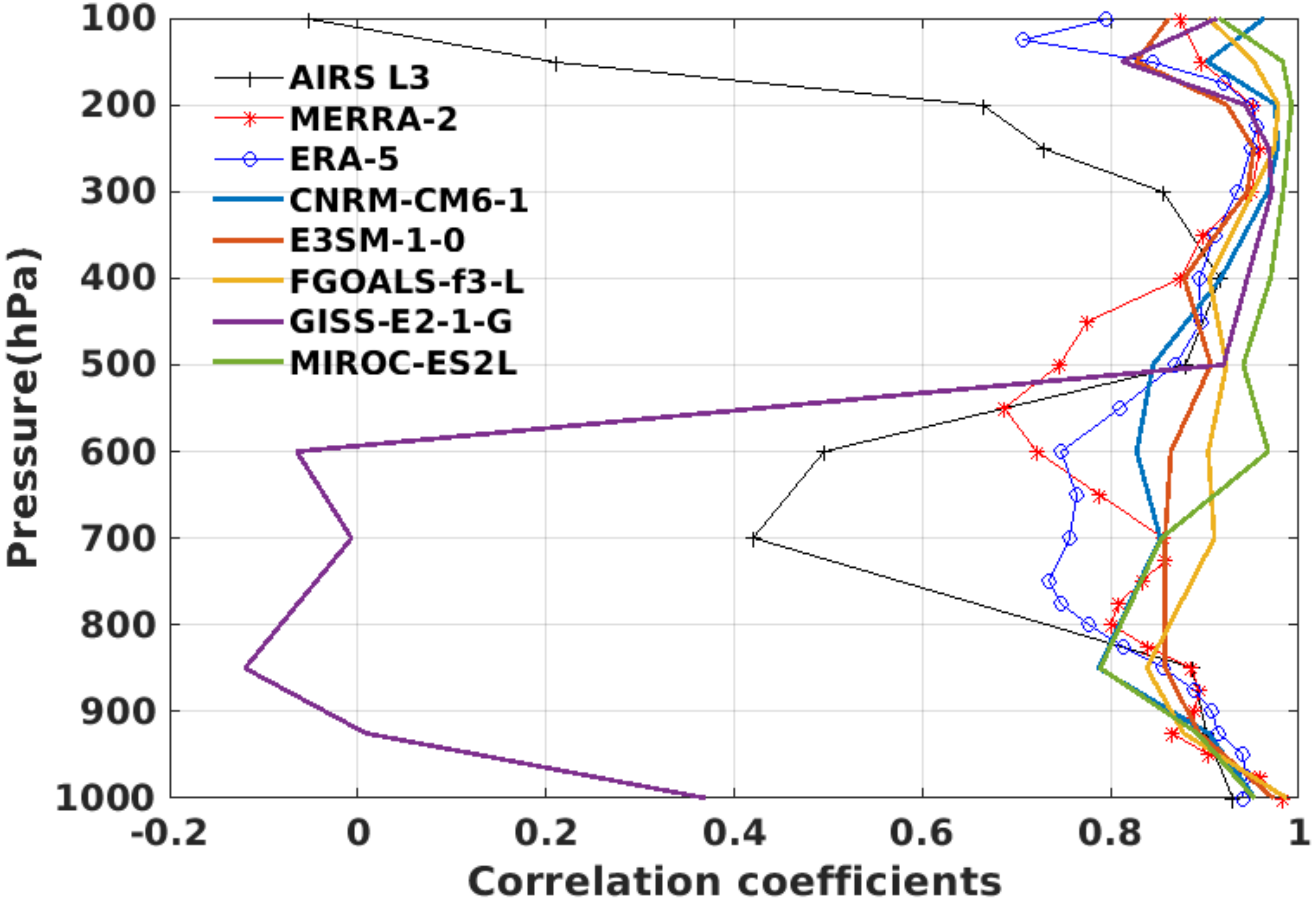


(Based on Huang et al., 2005 GRL; 1978-2000)

AM2: GFDL model for CMIP3
NCAR-NCEP/ERA40: 1st generation reanalysis

AIRS: the IR hyperspectral sounder aboard NASA Aqua satellite
MERRA-2/ERA-5: latest reanalysis

If we include a few more CMIP6 models …



(all AMIP simulations with observed SST and sea ice content)

At high temporal resolution …

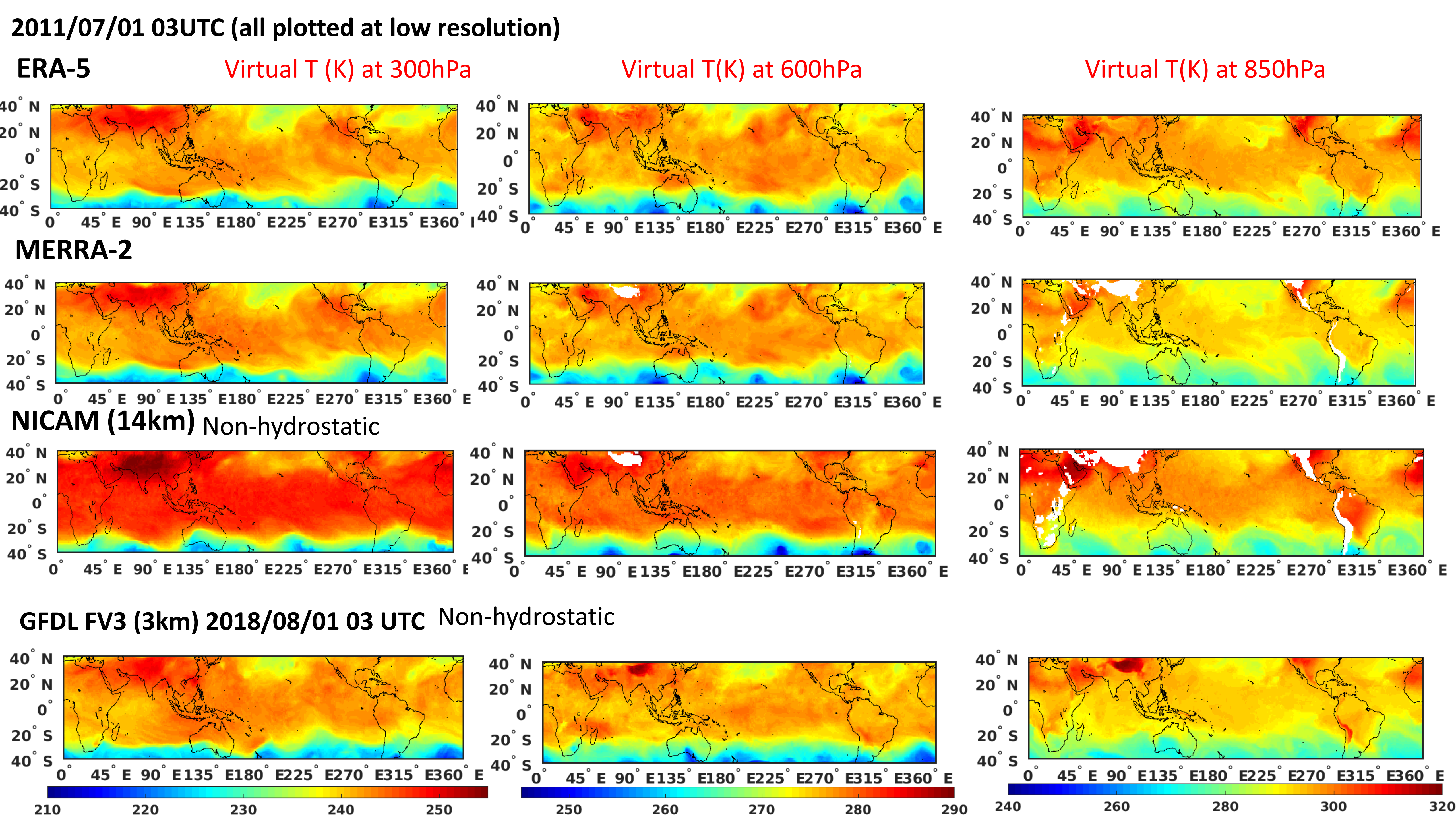
- Weak buoyancy gradient approximation (Charney, 1963; Sobel et al., 2001; Yang 2018)

  "the buoyancy gradient is negligible in the free troposphere without rotation because gravity waves can effectively smooth out buoyancy anomalies"

  which also leads to quasi-equilibrium tropical circulation approximation

- Buoyancy is measured by virtual temperature, $T_v = T\,(1+0.61q)$

- If $T_v\,(t|x, y, p)$ is fixed, $\langle T, q \rangle$ must be negatively correlated with each other.

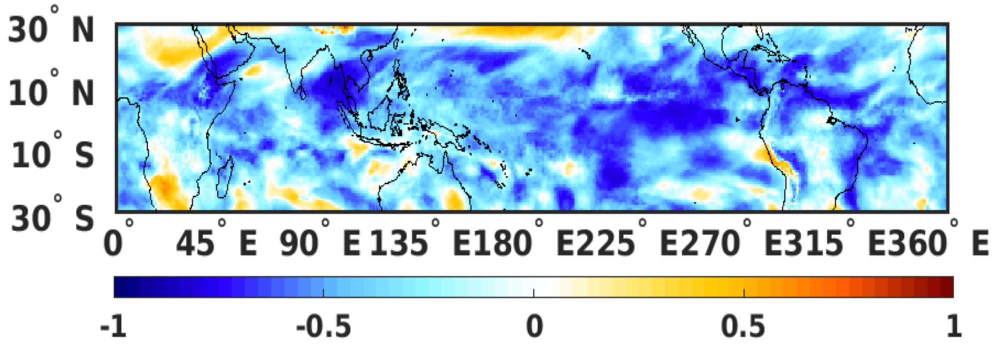

2011/07/01 03UTC (all plotted at low resolution)
ERA-5
Virtual T (K) at 300hPa
Virtual T(K) at 600hPa
Virtual T(K) at 850hPa
MERRA-2
NICAM (14km) Non-hydrostatic
GFDL FV3 (3km) 2018/08/01 03 UTC Non-hydrostatic
40° N
20° N
0°
20° S
40° S
0° 45° E 90° E 135° E 180° E 225° E 270° E 315° E 360° E
210 220 230 240 250
250 260 270 280 290
240 260 280 300 320

Year 2011, 6-hourly time series

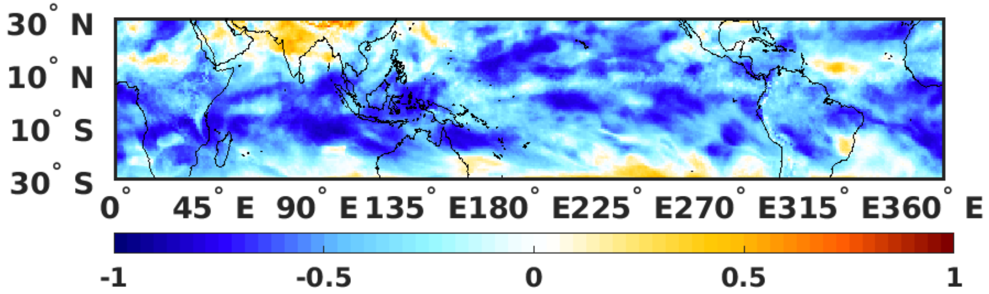
<T(t|x, y, 600 hPa), q(|x, y, 600 hPa)

ERA-5

Jan

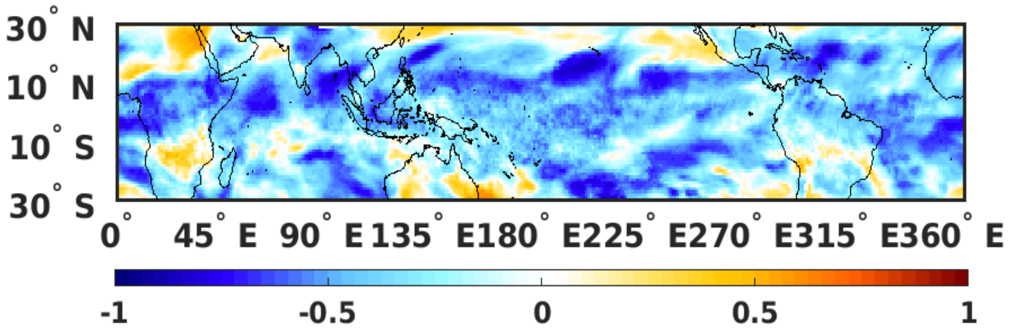


Jul

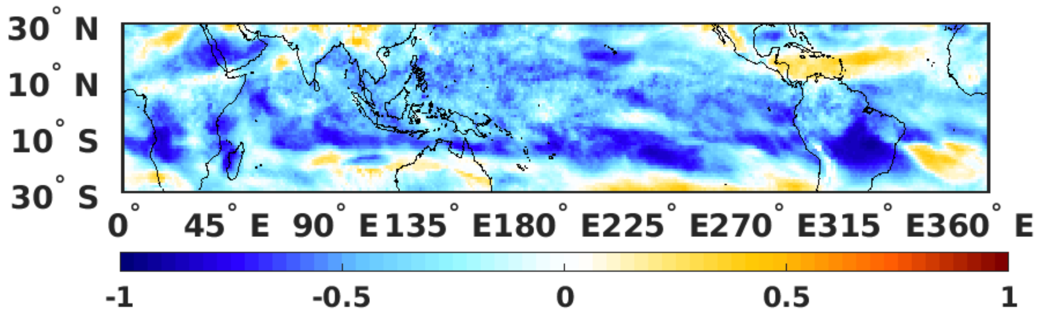


NICAM (14km)

Jan



Jul

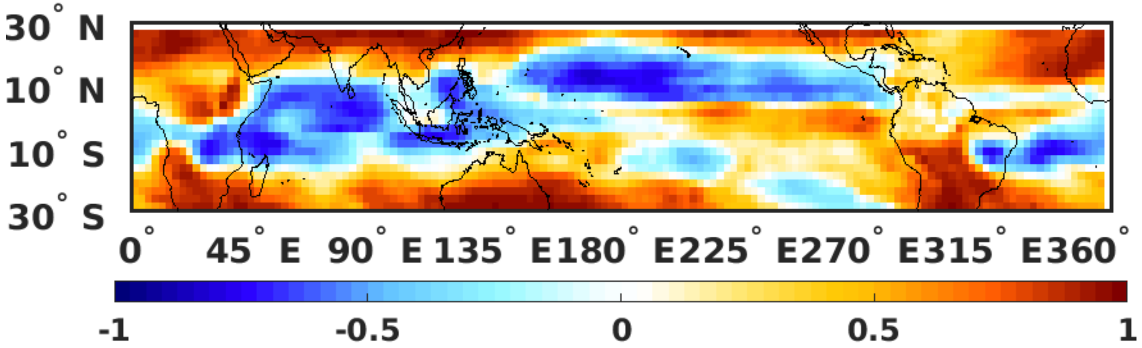


At 6-hourly resolution, positive correlation is limited and weak

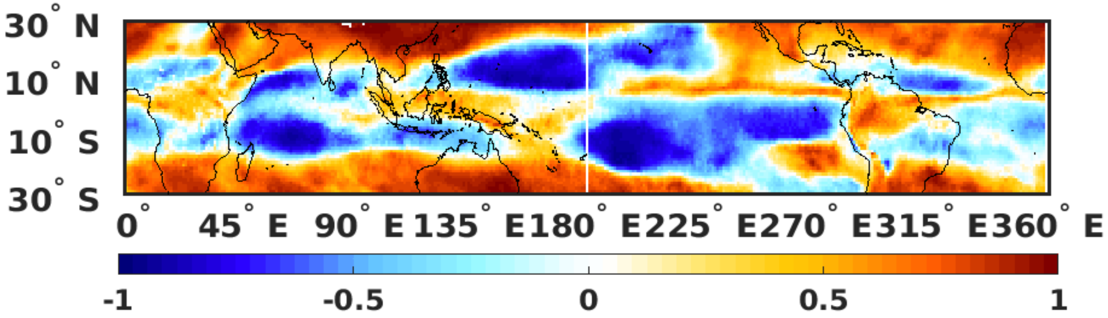
Year 2011, monthly-mean time series

$$\langle T(\bar{t}|x,y,600\ hPa), q(\bar{t}|x,y,600\ hPa)\rangle$$

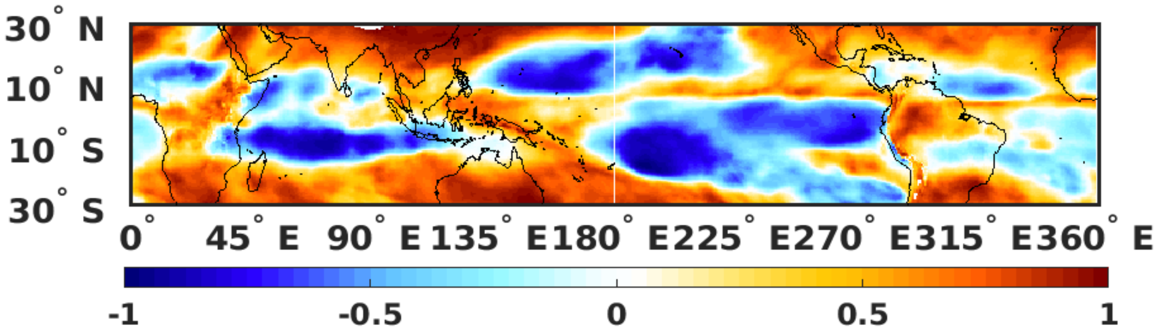
NICAM



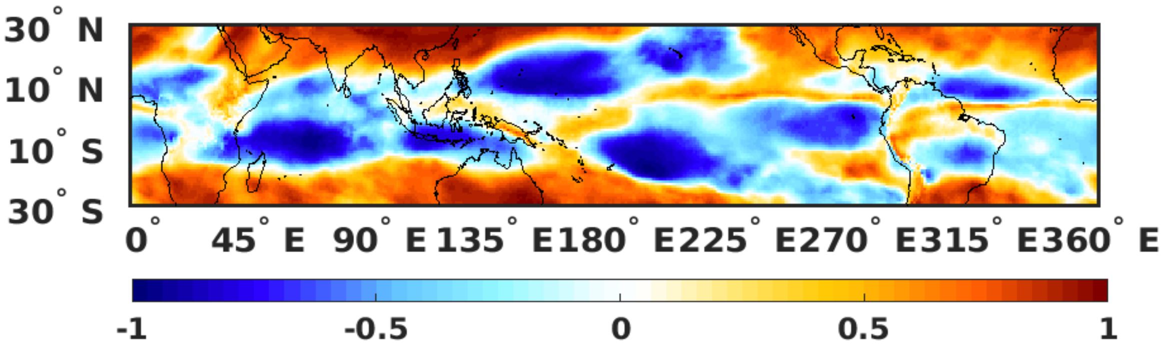
AIRS (obs)



MERRA-2 reanalysis



ERA-5 reanalysis



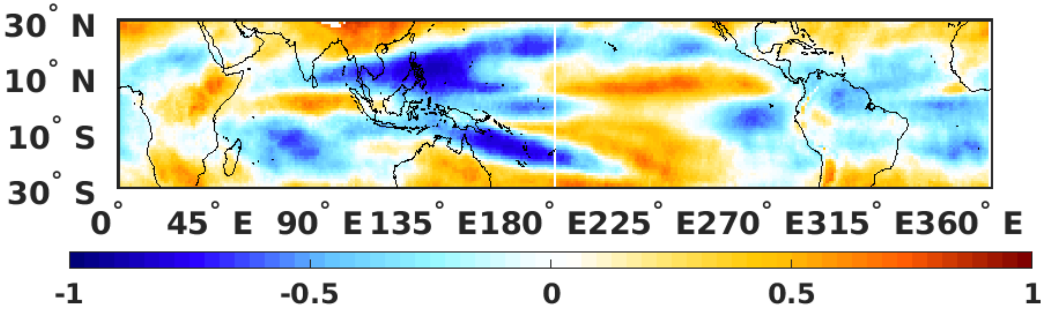
At monthly-mean resolution, strong bi-modal correlation coefficient

MICHIGAN

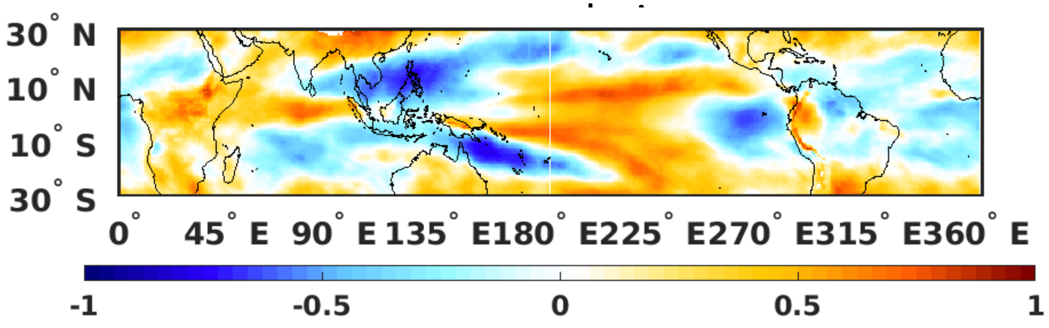
Year 2002-2021, 600 hPa, interannual anomalies of T and q

$$\langle T_a(\bar{t}|x, y, 600\ hPa), qa\ (\bar{t}|x, y, 600\ hPa)\rangle$$

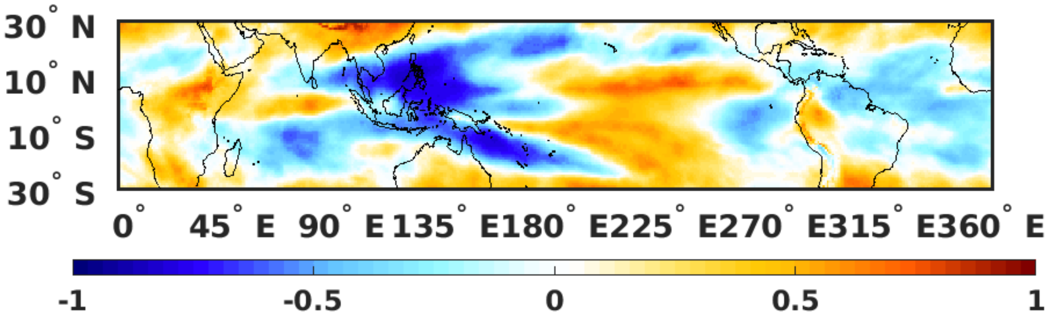
AIRS retrievals (obs)



MERRA-2

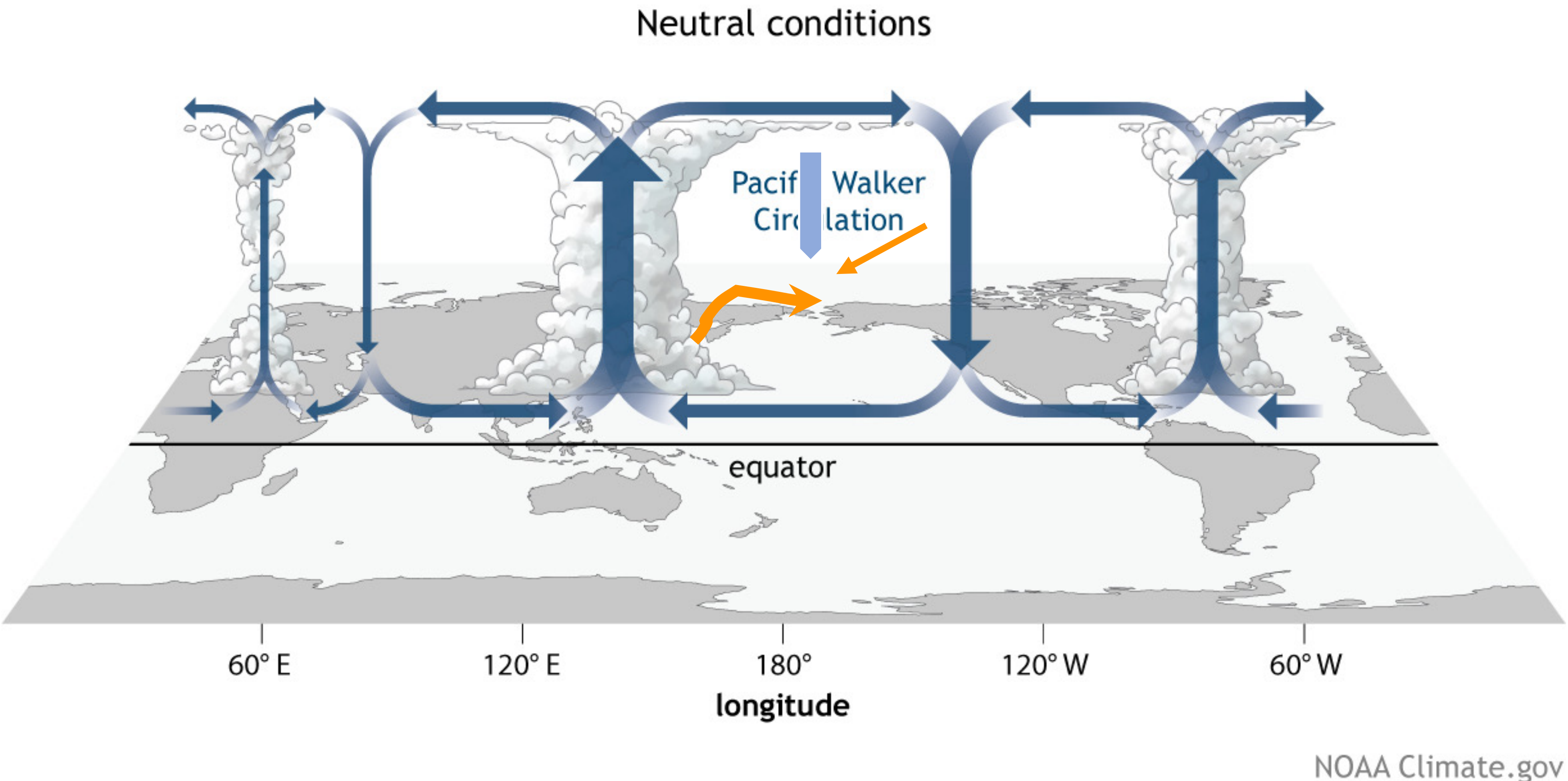


ERA-5 reanalysis



The complexity of humidity above the convective boundary layer and in the mid-troposphere

1. In the UT ("the last point of saturation")
2. In the PBL (homogenization by surface wind and evaporation)
3. Above the convective boundary layer? (lateral mixing, clear-sky descending, detrainment from cumulus, etc.)



How good can we measure mid-tropospheric T and q from space now?

Infrared sounders

- T: ~1K with 1-km resolution at a footprint ~10-20km
- q: ~15-20% with 2-km resolution at a footprint ~10-20km
- Dense sampling, very vulnerable to the presence of clouds
- Channel sensitivities vs. A priori: an issue often overlooked

Microwave sounders

- Usually coarser than IR sounders in vertical and horizontal resolutions
- Much less vulnerable to clouds

GPS occultations

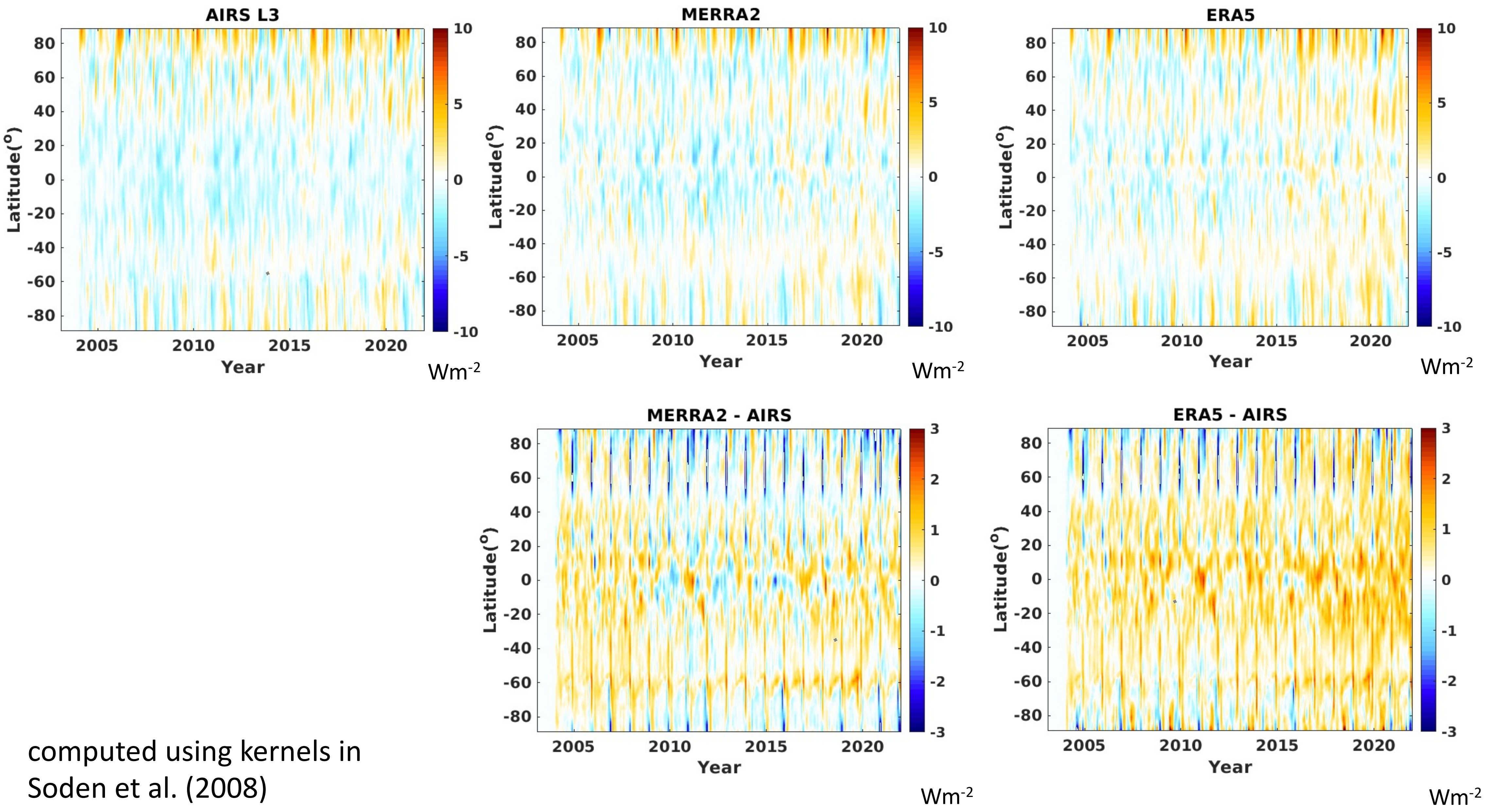
- Much more robust and accurate retrievals
- Sampling is limited; different viewing geometry, other info is needed to get q(p)

Is there a synergistic way to remotely observe all-sky q(p) from 800-600 hPa?

The implication for the EBAF-surface calculation

Humidity adjustment is needed to match up the TOA flux in the EBAF-surface calculation

All-sky OLR anomaly (deviation from 2003) due to $q_{anomaly}$ and $T_{anomaly}$ alone



computed using kernels in
Soden et al. (2008)

Discussions and reflections

- Tropical <T(t), q(t)> differs at different time and spatial scales: no spectral coherence, and physics interpretation differs
- Over 30 years, discrepancies among model and obs still exist in the <T, q> at the mid-troposphere and above the convective boundary layer
    - Reanalysis and observed T agree well. Humidity is a different story
    - What could we do in obs to help?

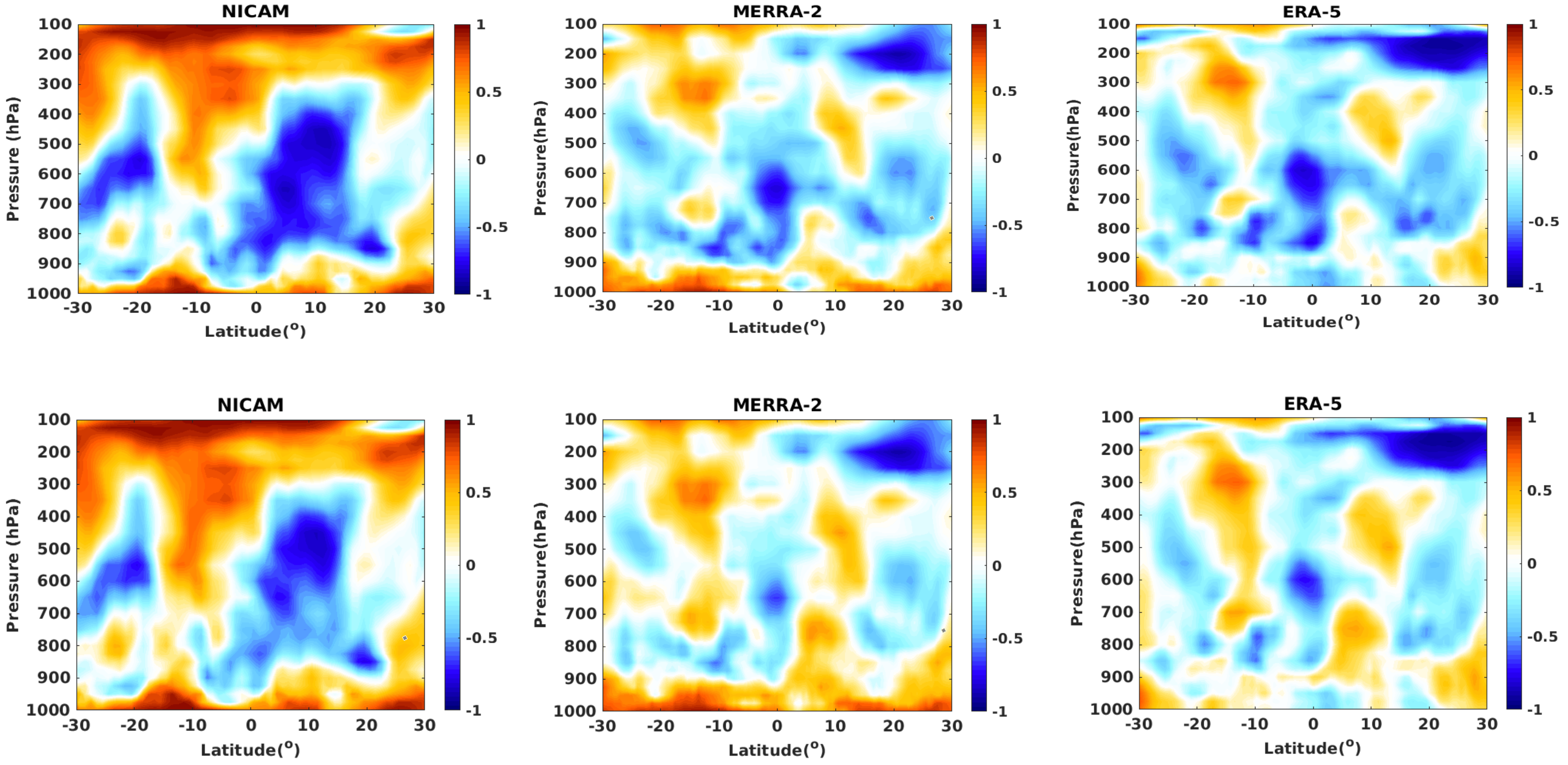
Thank You!

Back-up slides

Year 2011 (6-hourly for January only)

Corr. coef. between T and q

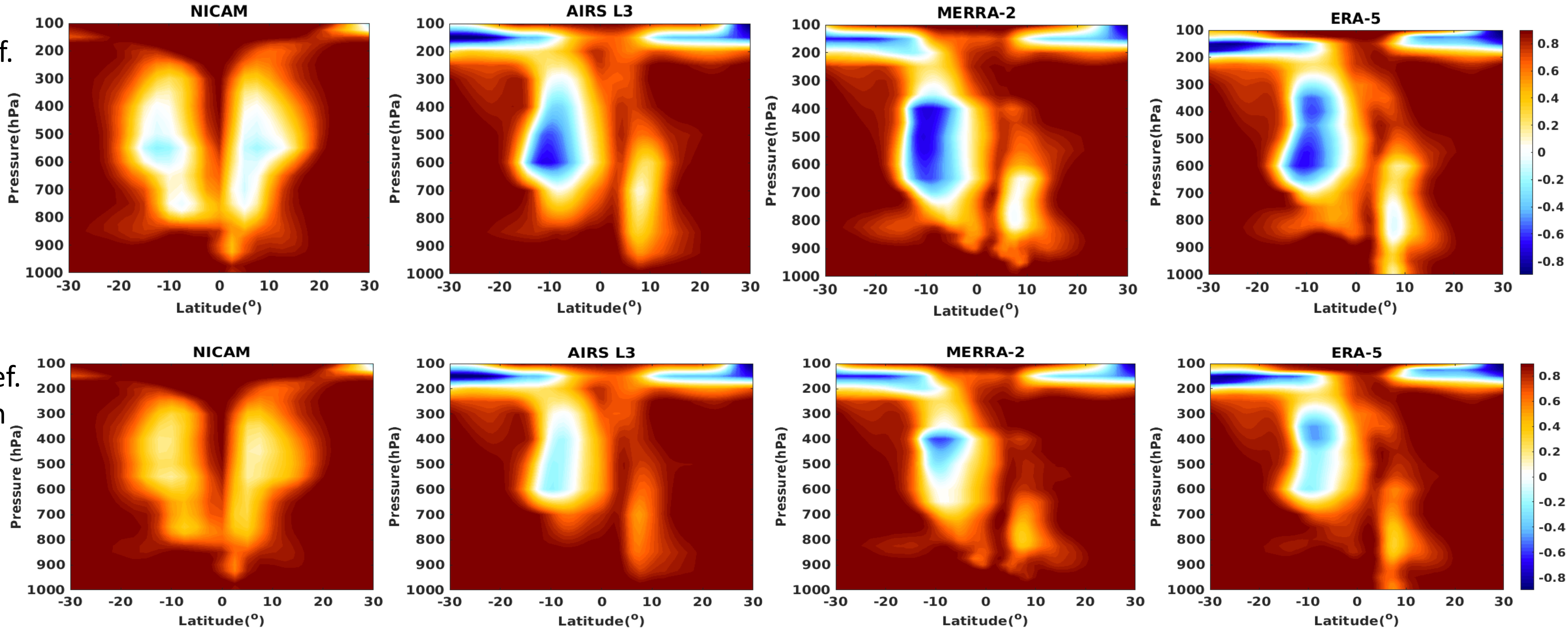
Corr. coef. between T_v and q



Year 2011 (Monthly—mean)

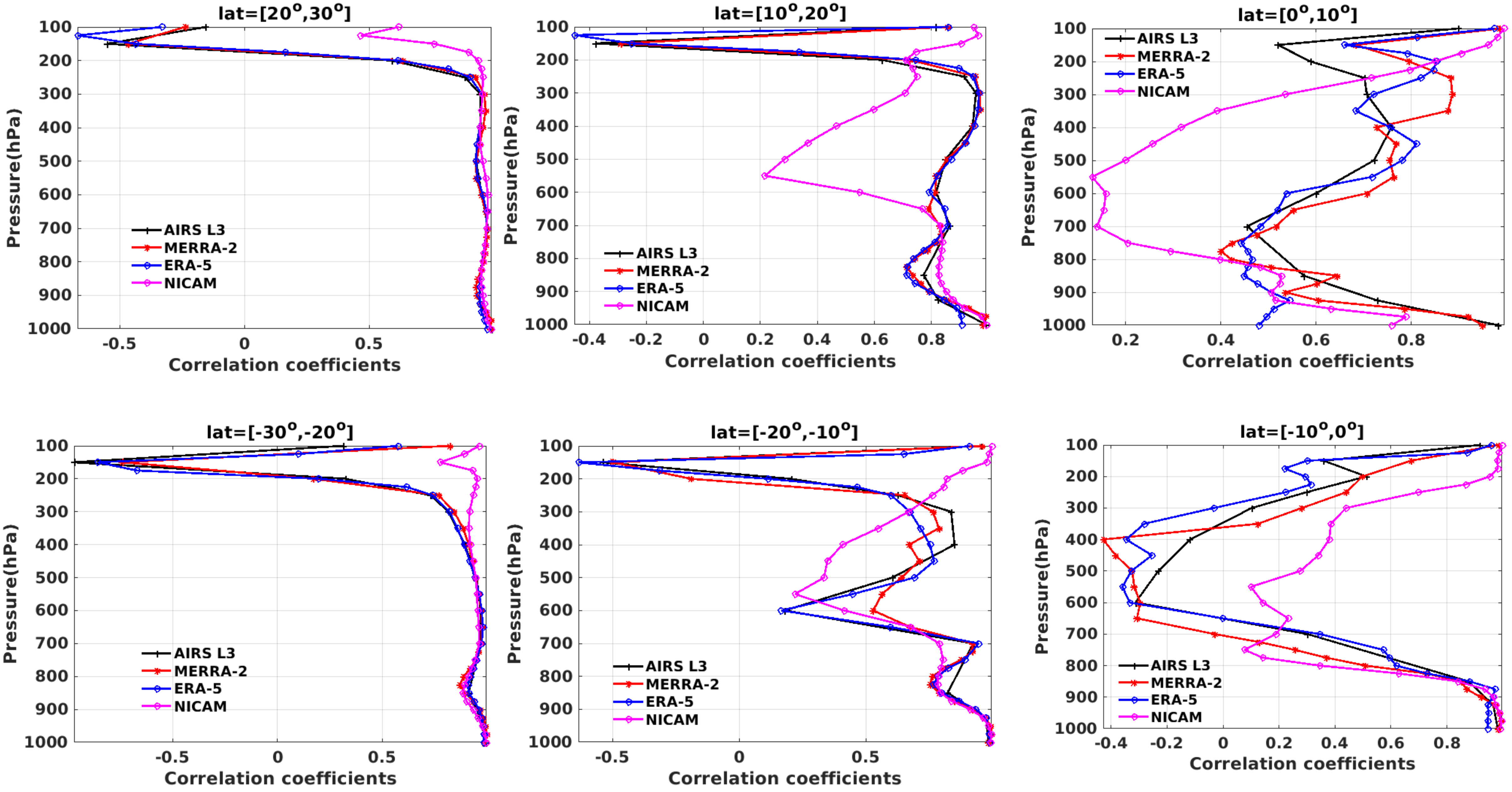
Corr. coef. between T and q

Corr. coef. between T_v and q



2011 monthly

Correlation coefficients between T and q



2011Jan 6-hourly

Correlation coefficients between T and q