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The impact of meteorological analysis uncertainties on the spatial scales resolvable in CO_2 model simulations

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The question

- Flux inversions (Bayesian synthesis, EnKF, 4Dvar) assimilate atmospheric CO_2 concentrations to solve for fluxes. Transport model is used as a strong constraint. It is not easy to account for errors in meteorological winds in this framework.
- Given the fact that meteorological analyses are imperfect, what is the impact of analysis errors on spatial scales that can be predicted in CO_2 model simulations?
- Approach: Use a coupled meteorological/transport model to study CO_2 predictability on weather/climate timescales

The tracer predictability problem

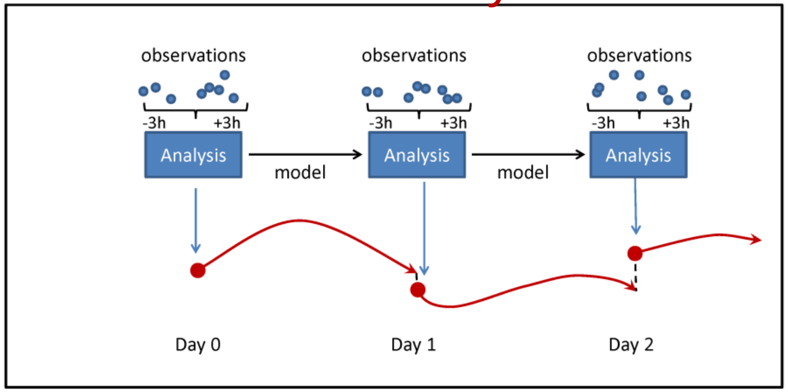
- Predictability (weather) refers to sensitivity to initial conditions
- CO_2 is a passive tracer so evolution governed by tracer transport equation. If the advecting winds are known, this is a linear equation and CO_2 is predictable.
- If the advecting winds are uncertain, then predictability of meteorology will influence tracer predictability
- We will look at predictability of CO_2 on:
  - Weather time scales
  - Seasonal time scales
  - As an upper limit on errors due to imperfect wind analyses

The Modeling System

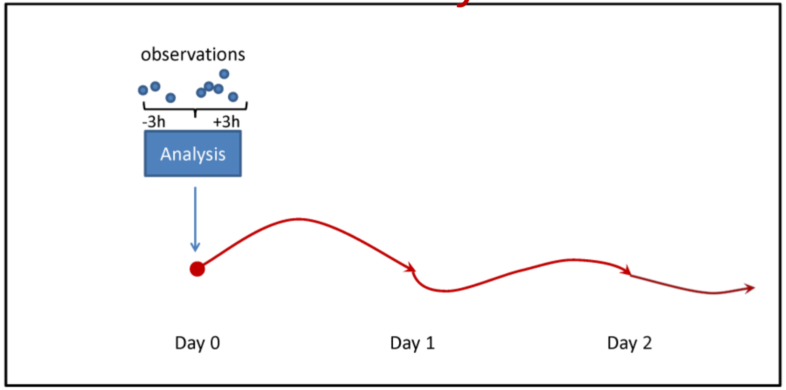
- Model based on ECCC operational weather forecast model, 0.9° × 0.9° × 80 levels (sfc to 0.1 hPa)
- Updates for mass conservation, mixing ratio wrt dry air, convective tracer transport, boundary layer model
- Time period: 2009-2010
- Initial condition: Jan. 1, 2009 0 UTC CT2010
- Fluxes: Posterior fluxes from NOAA ESRL CarbonTracker: CT2013B, CT2010
  http://carbontracker.noaa.gov

Experimental design

Reference cycle



Climate cycle

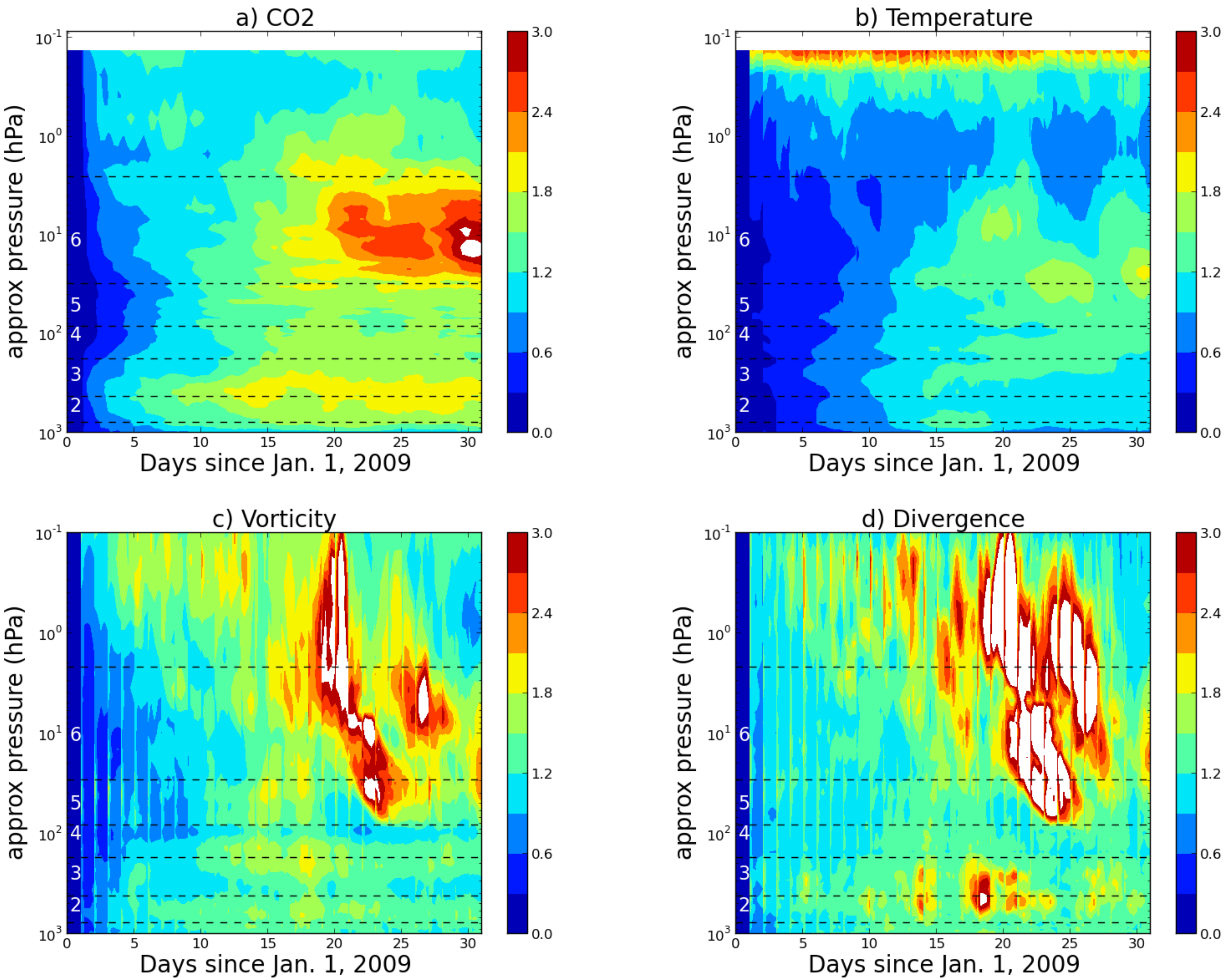


- Analyses constrain CO_2 transport using observed meteorology even with no CO_2 assimilation
- What if we don't use analyses (after the initial time) and replace them with 24h forecasts? → Climate cycle
- Climate cycle will drift from control cycle which uses analyses

Predictability error definition used

- Drift of climate cycle from reference cycle:
  - $E=(CO_2^{clim}-CO_2^{ref})$
- A measure of variability:
  - P = Sqrt[Global mean (zonal variance (E))]
- Normalize by variability in full state itself (at initial time):
  - P_0 = Sqrt[Global mean (zonal variance ($CO_2^{ref}(t_0)$))]
- Define Normalized Predictability error:
  - $N=P/P_0$
  - Dimensionless
  - Can compare different variables
  - N<<1 for small variability relative to state itself
  - Global measure (including tropics)

Normalized predictability error for Jan 2009

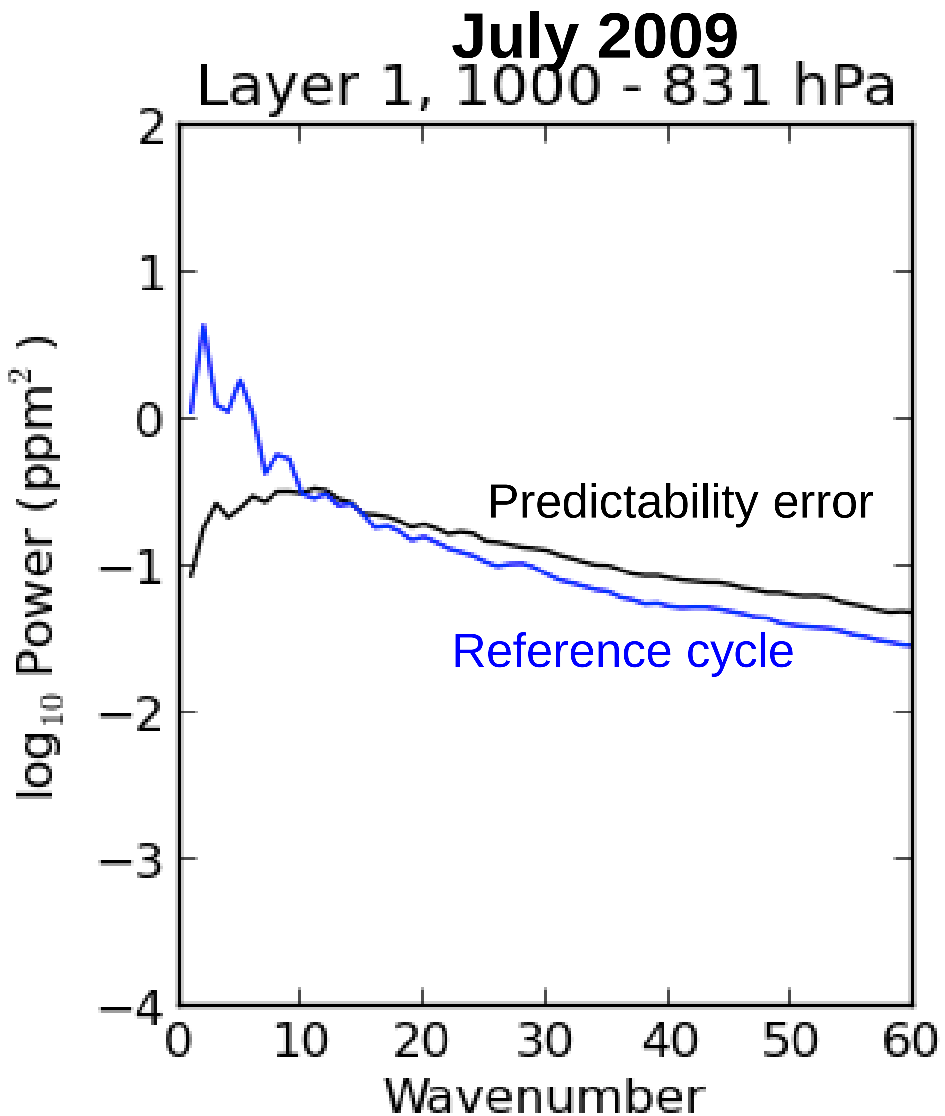


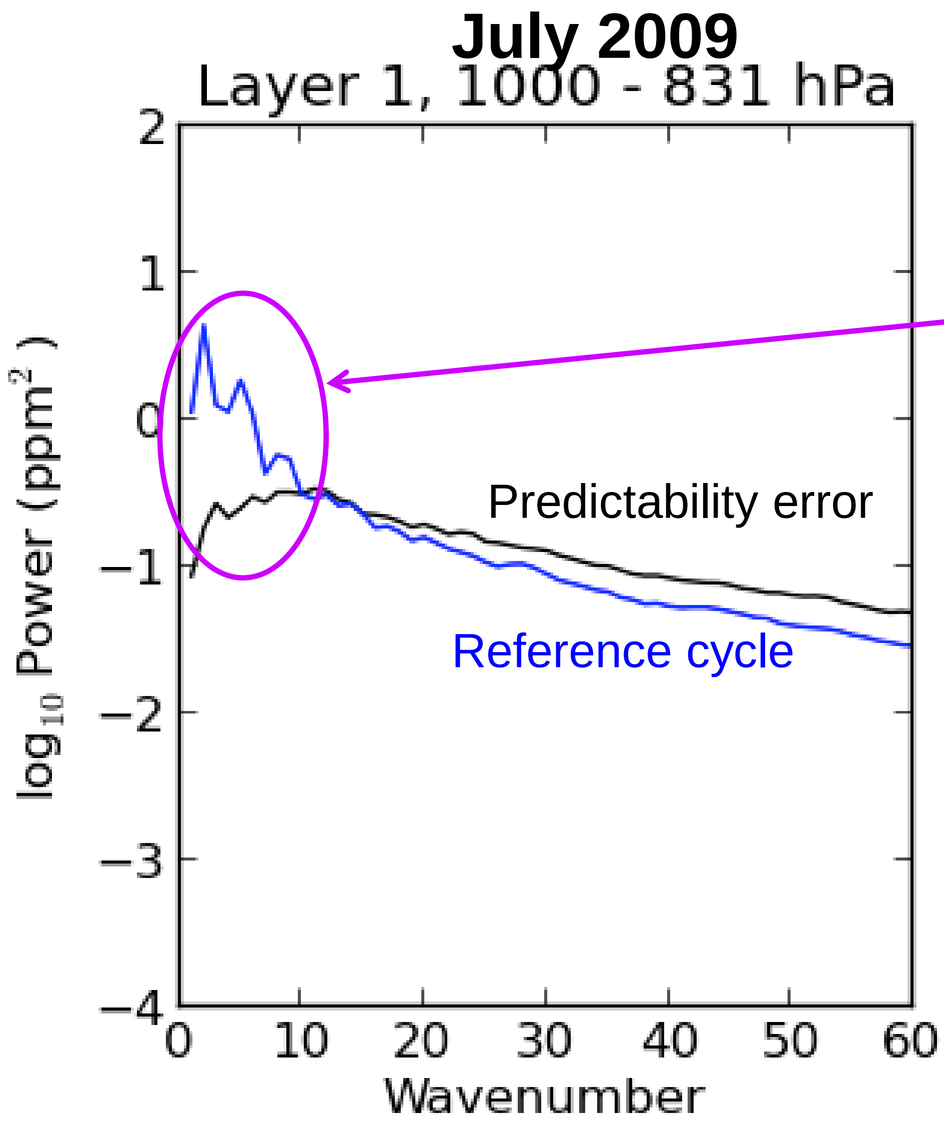
Weather time scales

- CO_2 predictability is short ~2 days in the free troposphere and follows pattern of wind field predictability. Temperature predictability is >10 days
- CO_2 predictability increases near the surface and in the lower stratosphere
- Generality of results:
  - Predictability results are model dependent (use of reference)
    - Relevant model details: Resolution, parameterizations, filtering
  - Arbitrary choice of initial state, and threshold of N<0.9 means numbers are not absolutely meaningful. Relative predictability is the result.
  - Very similar results for January 2010 (not shown) in the troposphere

Climate time scales: seasonal

- CO_2 evolution largely governed by boundary conditions (surface fluxes) not initial conditions
- Can we see predictability on longer (sub-seasonal to seasonal) time scales?
- Do a spherical harmonic decomposition of drift E and average over one month of spectra, and over 12 model levels


July 2009
Layer 1, 1000 - 831 hPa
Predictability error
Reference cycle
log10 Power (ppm2)
Wavenumber
2
1
0
−1
−2
−3
−4
0
10
20
30
40
50
60

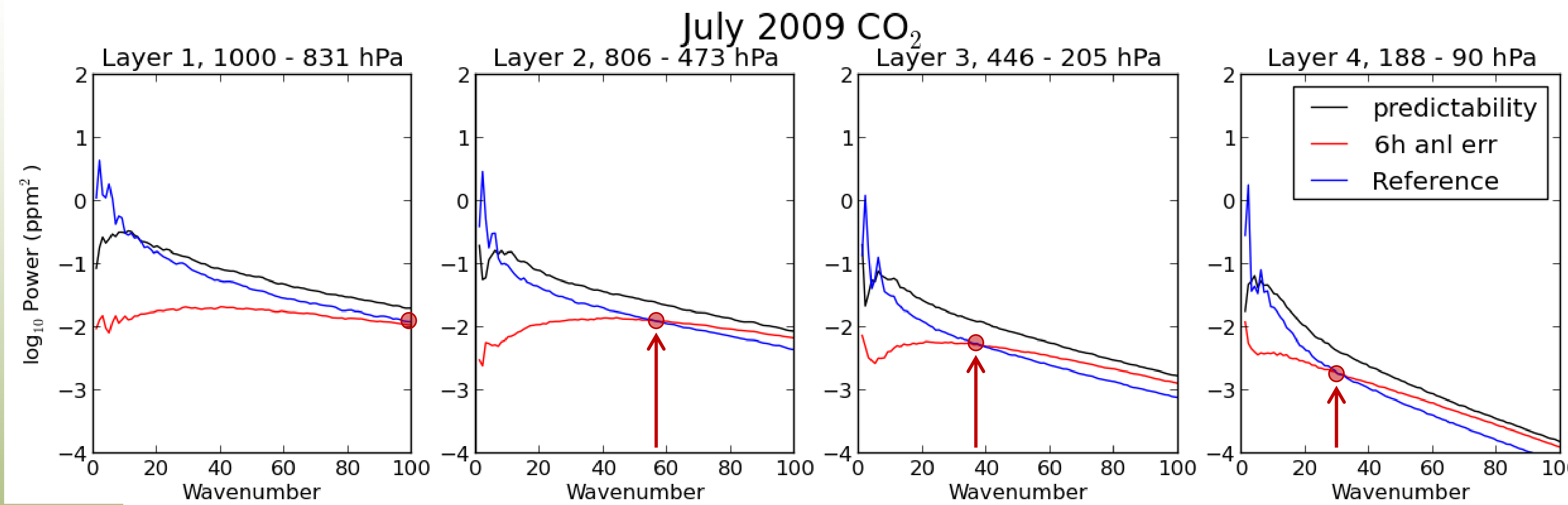


Largest scales are predictable in July

Where does this predictability come from?

- CO_2 fluxes
- Land/ocean surface

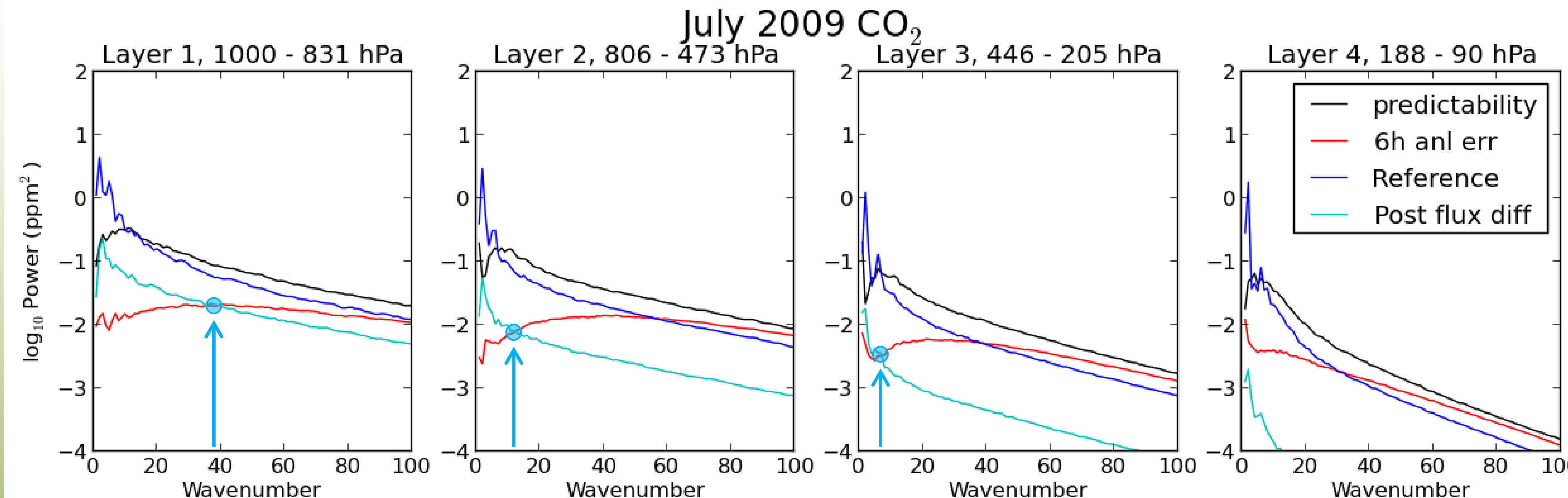
Impact of meteorological analysis uncertainty



Climate cycle is an extreme case. In reality analyses keep our cycle close to observations. But analyses are not perfect. What is the impact of analysis error on CO_2 spatial scales? Proxy: Cycle with analysis 6h early.

- Resolve a lot more scales compared to predictability limit
- BUT, power spectrum asymptotes to predictability spectrum. For smaller spatial scales, we don't gain much over predictability error.
- For some wavenumber, the power in this error equals that in the state itself (red arrows). *There is a spatial scale below which CO_2 is not resolved due to analysis uncertainty.* This spatial scale increases with altitude.

Impact of posterior flux differences



What spatial scales are different when using 2 posterior fluxes (CT2010, CT2013B)? Look at cyan curve.

- Largest scales are different in the 2 posterior fluxes
- Compared to power in CO_2 difference from shifting analyses, only largest scales are resolved.
- The difference in fluxes is less apparent at higher altitudes because both posteriors used surface observations only

Conclusions

- Predictability of CO_2 is shorter than that of the temperature field and is consistent with that of the wind field
- Long time scale predictability exists for the largest spatial scales and is due to long time scale memory in surface fluxes and in the land and ocean surface fields (Not shown today)
- The fact that analyses are imperfect means that some spatial scales in CO_2 simulations are not resolved
- There is a spatial scale below which CO_2 is not resolved due to the presence of analysis uncertainty. This spatial scale gets larger with altitude.
- Differences in 2 posterior fluxes are greatest at very large scales near the surface.
- Model error due to lack of convective tracer transport is largest at large spatial scales and is generally smaller than that due to analysis uncertainty (Not shown today)

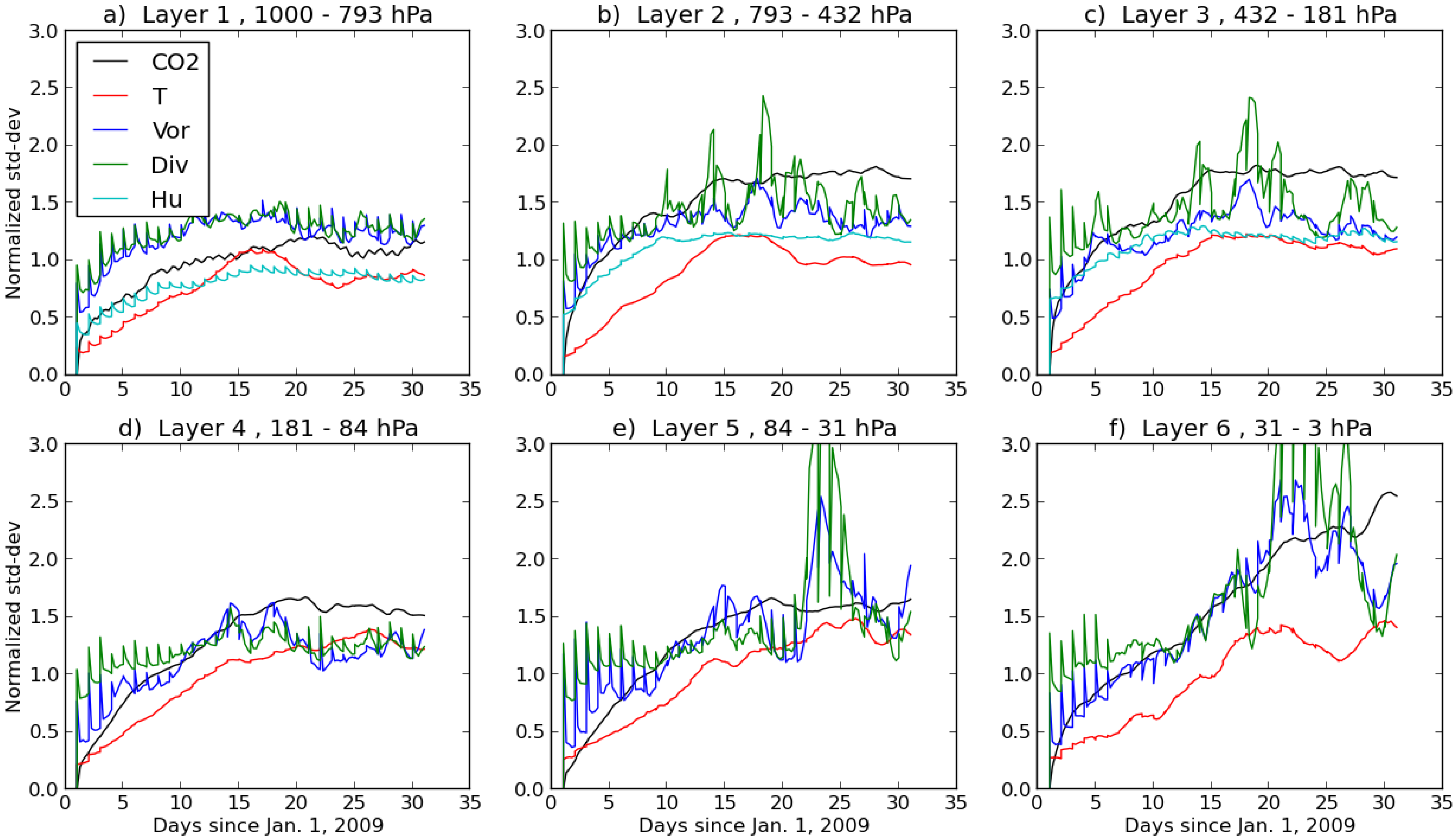
EXTRA SLIDES

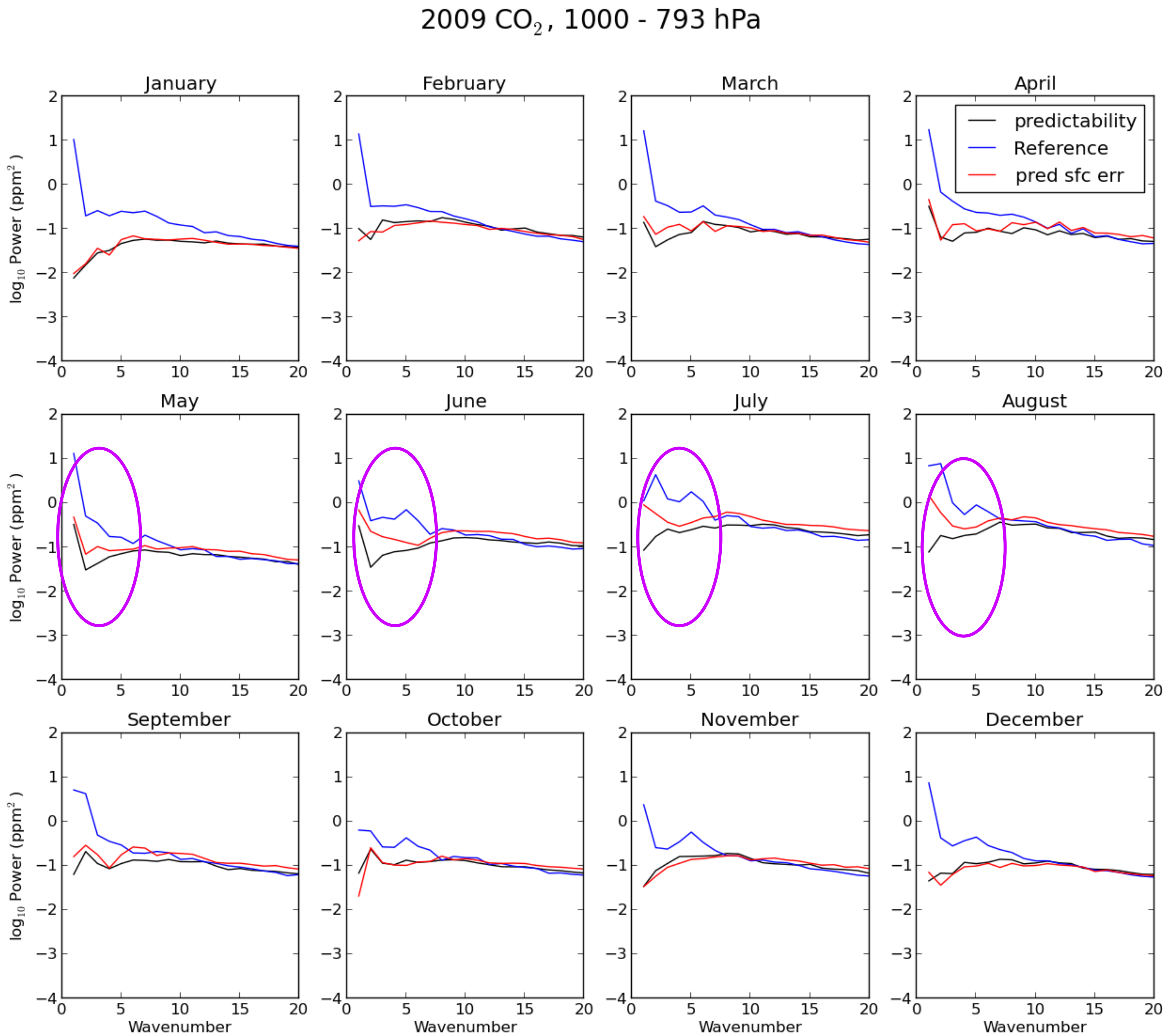
Implications for flux inversions

$$J(\overset{\text{flux}}{\overset{\downarrow}{S}})=\frac{1}{2}\left(S-\overset{\text{Prior flux}}{\overset{\downarrow}{S^b}}\right)^T \mathbf{B}^{-1}\left(S-S^b\right)+\frac{1}{2}\left(\overset{\text{conc obs}}{\overset{\downarrow}{c^{obs}}}-\underset{\text{Spatial interpolation}}{H}\left[\underset{\text{Forecast model}}{c^f(S)}\right]\right)^T \mathbf{R}^{-1}\left(c^{obs}-H\left[c^f(S)\right]\right)$$

- Contribution of meteorological analysis error to transport error increases with decreasing spatial scale
- Contribution of meteorological analysis error to transport error has spatial correlations (error spectrum not flat). So **R** needs to account for spatial correlations.
- Validity of transport model trajectory during assimilation window depends on spatial scale.

Normalized predictability error

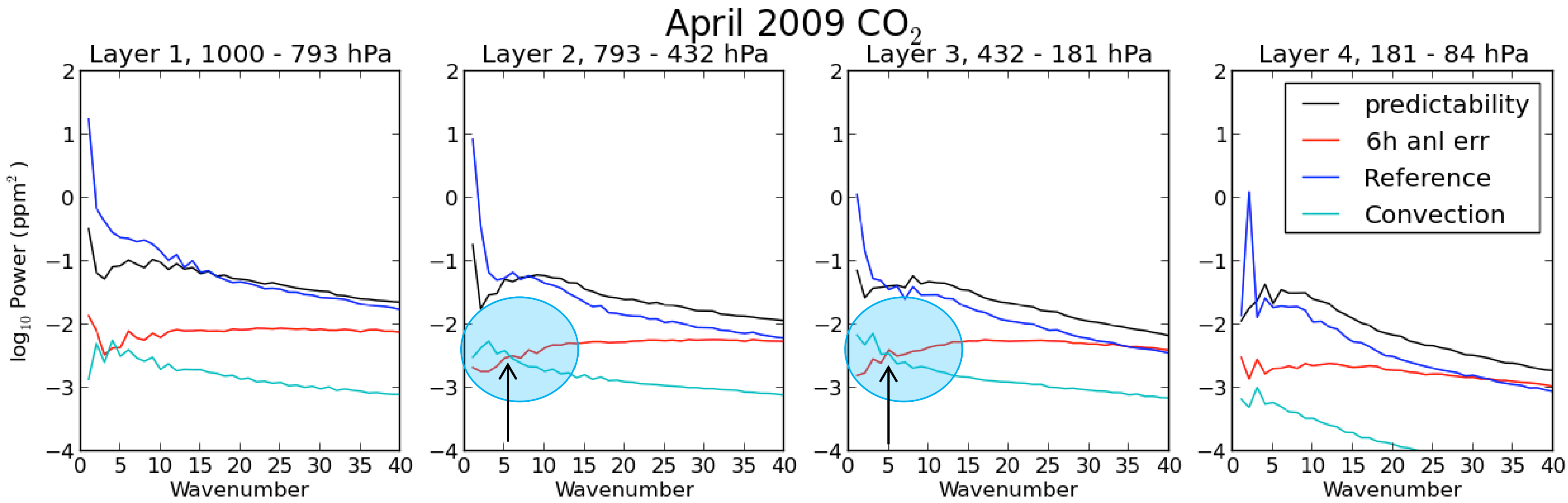




Land and ocean surface affects CO_2 predictability

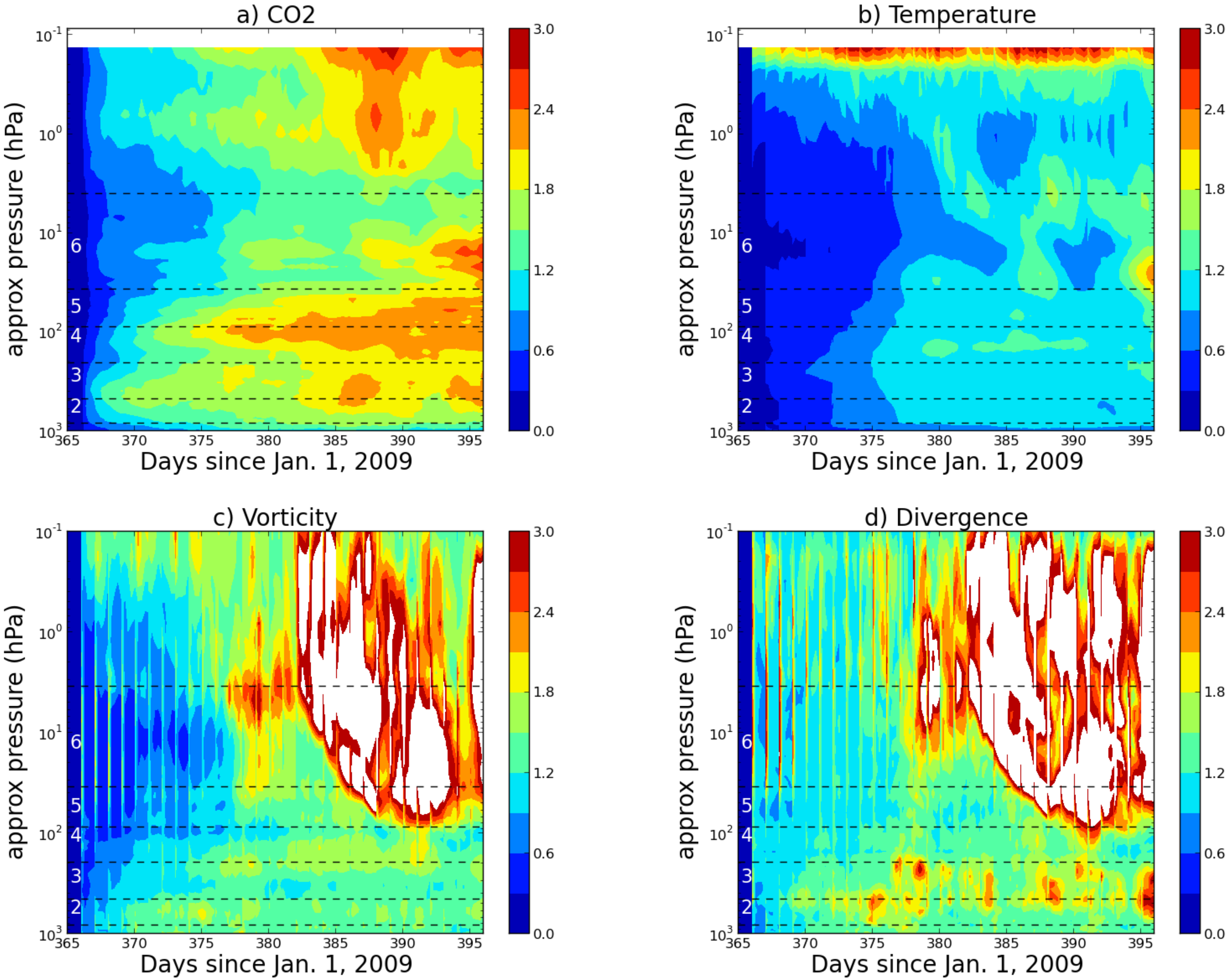
Impact of model error on CO_2

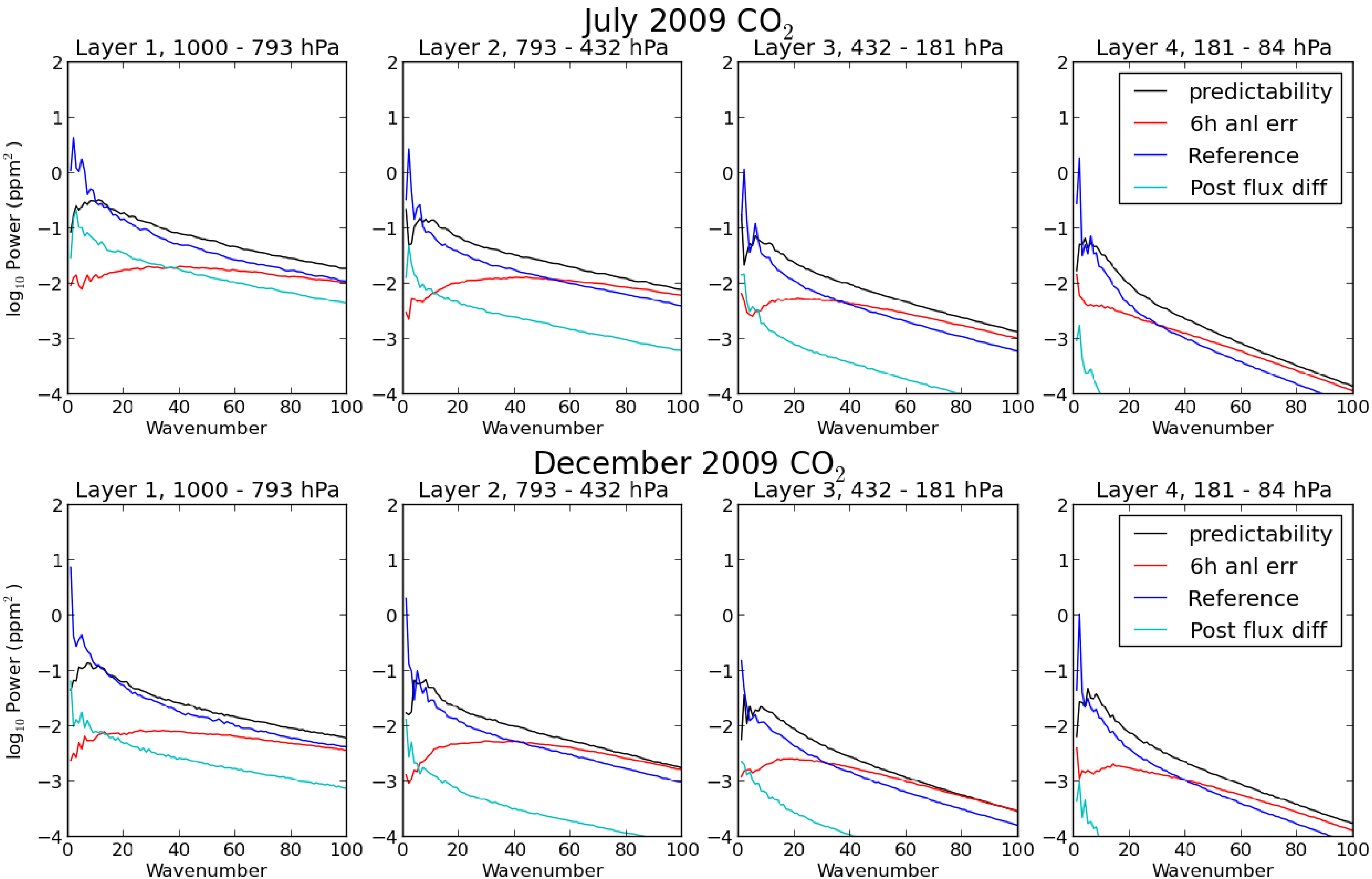
Impact of convective tracer transport



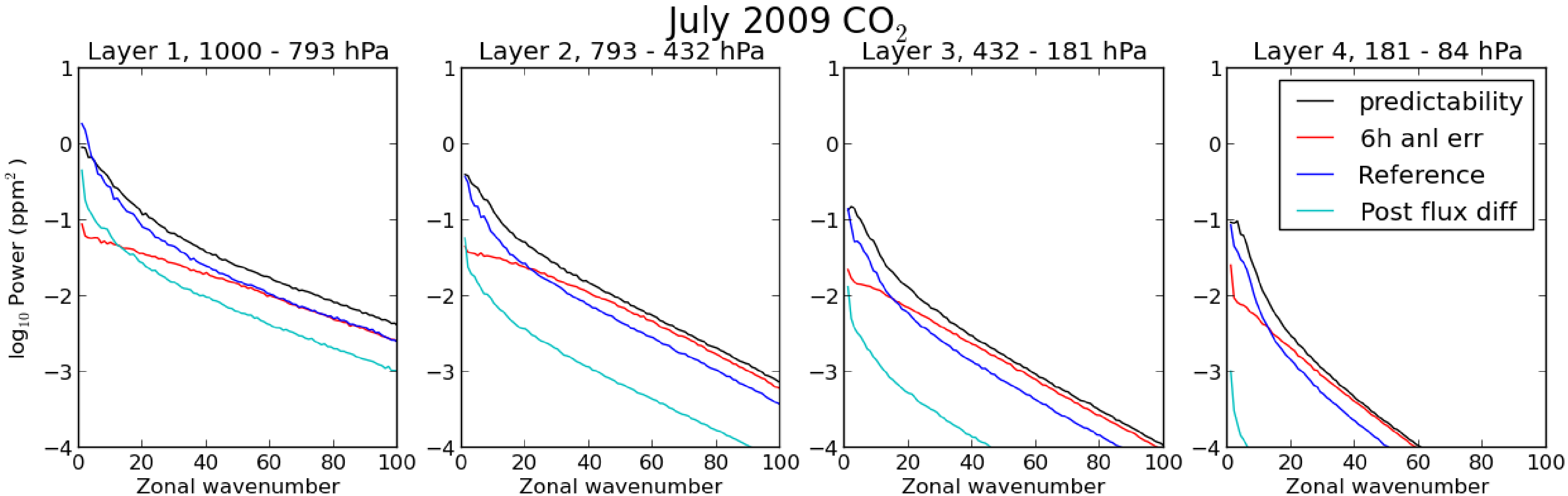
Change in CO_2 from adding convective tracer transport exceeds that due to shifted analysis in mid troposphere, for wavenumbers < 5

Normalized predictability error for Jan 2010





July 2009 CO_2
Layer 1, 1000 - 793 hPa
Layer 2, 793 - 432 hPa
Layer 3, 432 - 181 hPa
Layer 4, 181 - 84 hPa
$\log_{10}$ Power (ppm^2)
Wavenumber
predictability
6h anl err
Reference
Post flux diff
December 2009 CO_2
Layer 1, 1000 - 793 hPa
Layer 2, 793 - 432 hPa
Layer 3, 432 - 181 hPa
Layer 4, 181 - 84 hPa
$\log_{10}$ Power (ppm^2)
Wavenumber
predictability
6h anl err
Reference
Post flux diff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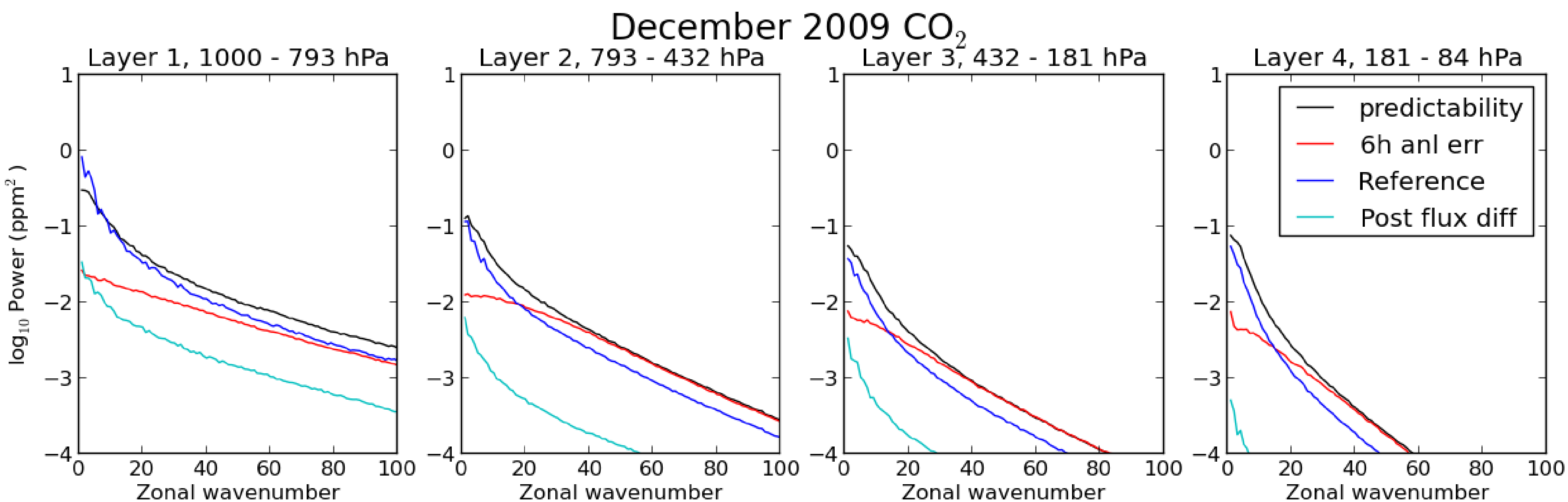
$\log_{10}$ Power (ppm^2)
Zonal wavenumber
predictability
6h anl err
Reference
Post flux diff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2009 CO_2, 1000 - 793 hPa