Climate model wind stress biases in the northern low latitudes from a momentum balance perspective.

Isla Simpson[1]

Julio Bacmeister[1], Irina Sandu[2], Mark Rodwell[2]

(1) Climate and Global Dynamics Laboratory, National Center for Atmospheric Research

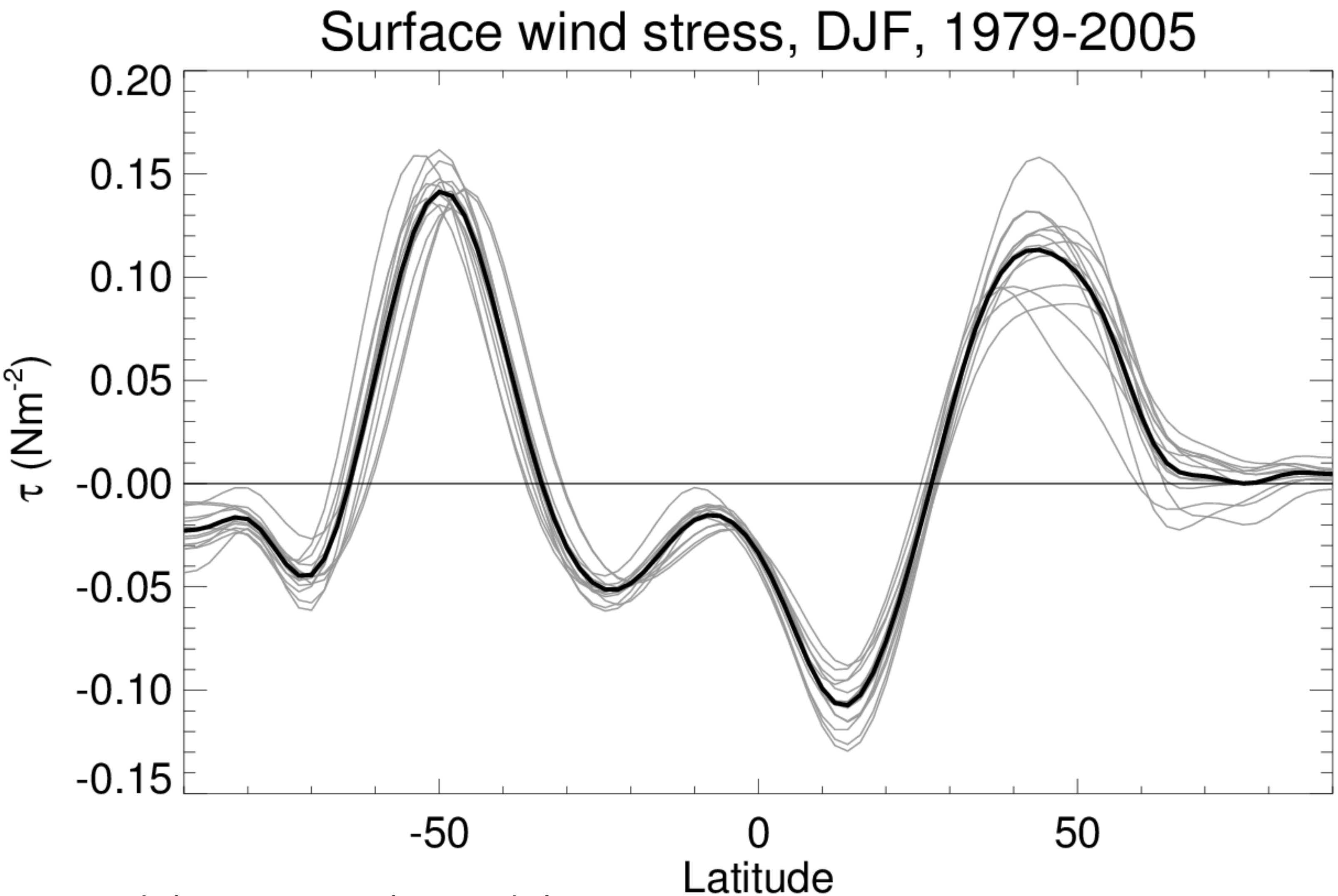
(2) European Centre for Medium Range Weather Forecasts

Surface Wind Stress

- CMIP5 variable (*tauu*) = surface downward eastward wind stress (excluding gravity wave drag surface stress)
- ERA-Interim variable = Eastward turbulent surface stress. (i.e. not including GWD surface stress)

Sign Convention: will show the downward stress
i.e. -1 x forcing on the atmosphere

Zonal mean surface wind stress during DJF, 1979-2005

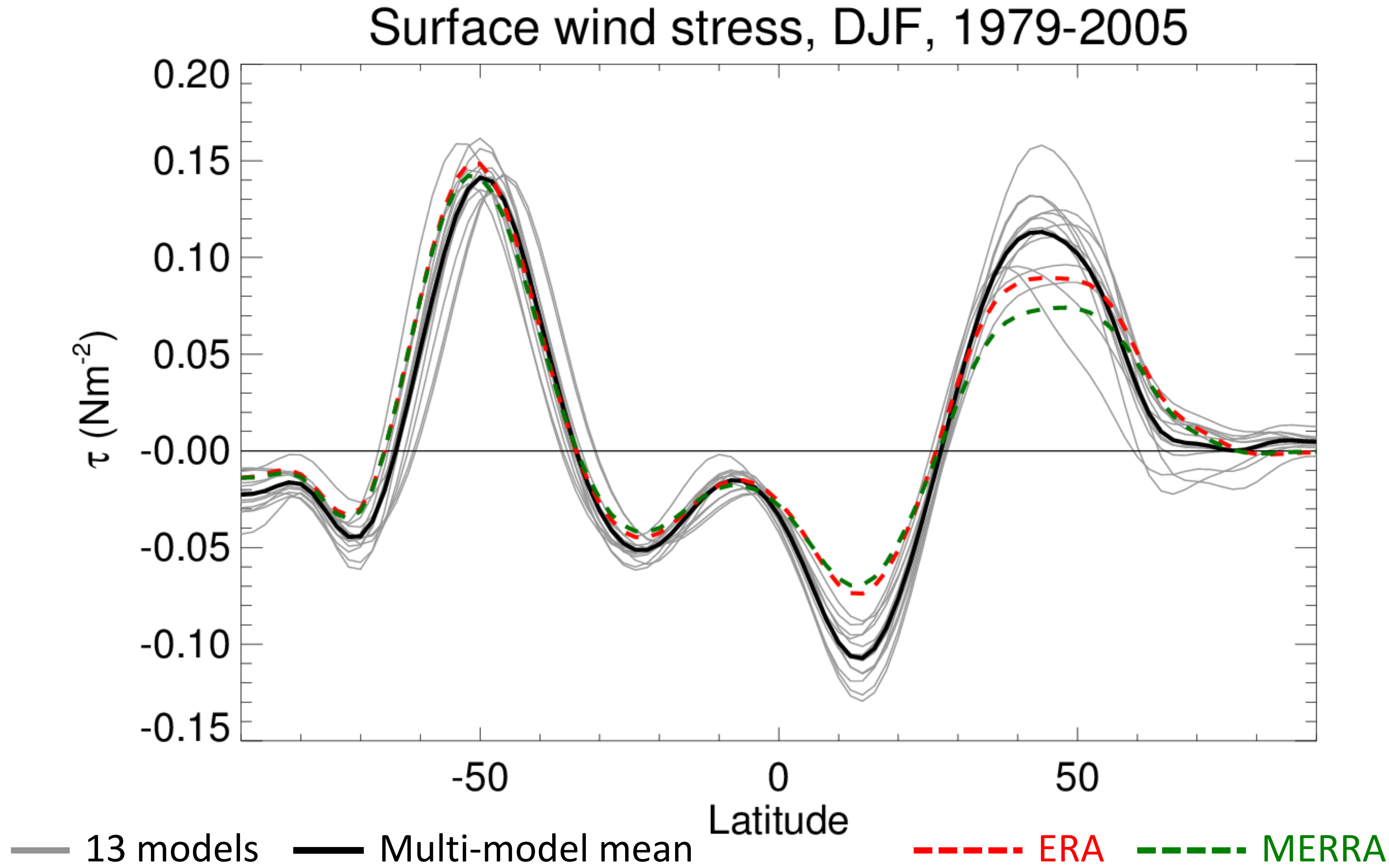


13 models — Multi-model mean

(Coupled historical simulations)

Simpson, Shaw and Seager, J. Clim. (2014)

Zonal mean surface wind stress during DJF, 1979-2005



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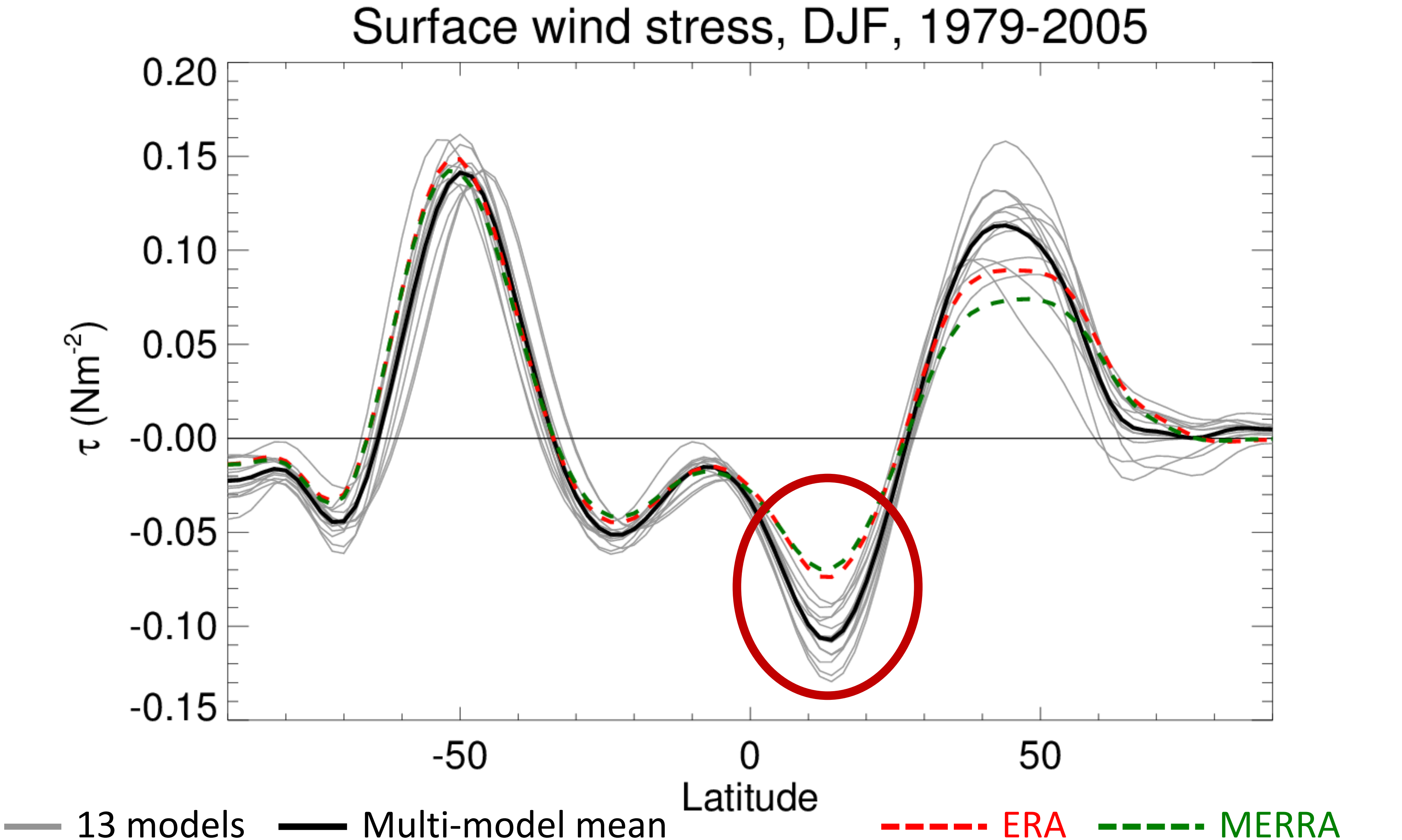

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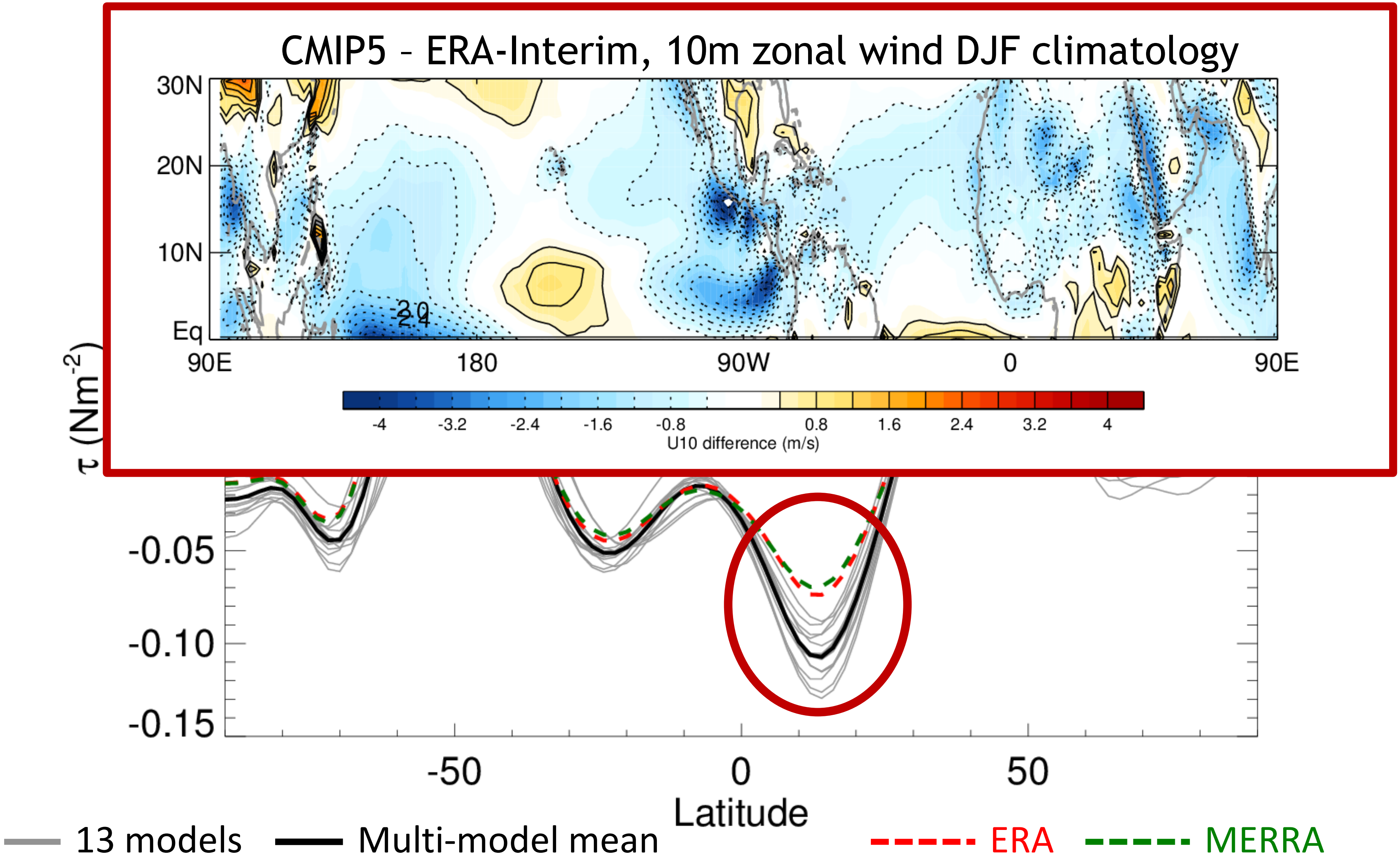
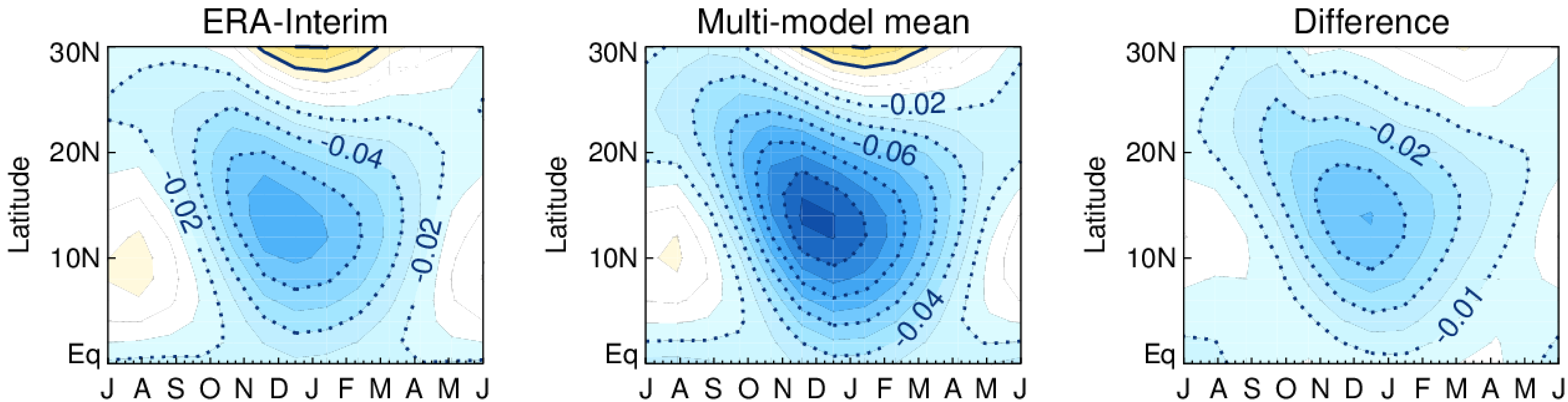


Simpson, Shaw and Seager, J. Clim. (2014)

Seasonal evolution of low latitude wind stress differences

ERA-Interim vs multi-model mean



ERA-Interim

CMIP5

CMIP5 – ERA-Interim

What can we learn about these zonal mean surface wind stress differences from the vertically integrated momentum balance?

The Vertically Integrated Momentum Balance

The zonal momentum equation on a pressure surface:

$$\frac{\partial u}{\partial t} = fv - \frac{1}{acos\varphi}\frac{\partial \Phi}{\partial \lambda} - \frac{1}{acos^2\varphi}\frac{\partial (uvcos^2\varphi)}{\partial \varphi} - \frac{1}{acos\varphi}\frac{\partial (uu)}{\partial \lambda} - \frac{\partial (u\omega)}{\partial p} + F_u + X$$

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Coriolis
Force

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Coriolis Force

Geopotential gradient

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Tendency from boundary layer turbulence

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Tendency from other parameterizations (GWD, horizontal diffusion etc)

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Coriolis Force

Geopotential gradient

Tendency from boundary layer turbulence

Calculate the mass weighted vertical integral at each lon and lat

$$[\,.\,] = \frac{1}{g}\int_0^{p_s(\lambda,\varphi,t)} (\,.\,)dp$$

Tendency from other parameterizations (GWD, horizontal diffusion etc)

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Calculate the mass weighted vertical integral at each lon and lat

$$[\,.\,] = \frac{1}{g}\int_0^{p_s(\lambda,\varphi,t)} (\,.\,)dp$$

Then take the zonal mean.

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Don't have this
for CMIP5

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$$[F_u] = -\tau_u$$

Don’t have this for CMIP5

The Vertically Integrated Momentum Balance

The zonal momentum equation on a pressure surface:

$-u_s\omega_s$

$$\cancel{\frac{\partial u}{\partial t}} = fv - \frac{1}{a\cos\varphi}\frac{\partial\Phi}{\partial\lambda} - \frac{1}{a\cos^2\varphi}\frac{\partial(uv\cos^2\varphi)}{\partial\varphi} - \frac{1}{a\cos\varphi}\frac{\partial(uu)}{\partial\lambda} - \frac{\partial(u\omega)}{\partial p} + F_u + X$$

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$$[fv]-\left[\frac{1}{a\cos\varphi}\frac{\partial\Phi}{\partial\lambda}\right]-\left[\frac{1}{a\cos^2\varphi}\frac{\partial(uv\cos^2\varphi)}{\partial\varphi}\right]-\left[\frac{1}{a\cos\varphi}\frac{\partial(uu)}{\partial\lambda}\right]-u_s\omega_s=\tau_u$$

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Upon taking the zonal mean…

The Vertically Integrated Momentum Balance

$$[fv] - \left[\frac{1}{acos\varphi}\frac{\partial\Phi}{\partial\lambda}\right] - \left[\frac{1}{acos^2\varphi}\frac{\partial(uvcos^2\varphi)}{\partial\varphi}\right] - \left[\frac{1}{acos\varphi}\frac{\partial(uu)}{\partial\lambda}\right] - u_s\omega_s = \tau_u$$

Mountain Torque (M)

Upon taking the zonal mean…

The Vertically Integrated Momentum Balance

$$[fv] - \left[\frac{1}{acos\varphi}\frac{\partial\Phi}{\partial\lambda}\right] - \left[\frac{1}{acos^2\varphi}\frac{\partial(uvcos^2\varphi)}{\partial\varphi}\right] - \cancel{\left[\frac{1}{acos\varphi}\frac{\partial(uu)}{\partial\lambda}\right]} - \cancel{u_s\omega_s} = \tau_u$$

small small

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Upon taking the zonal mean…

The Vertically Integrated Momentum Balance

$$[fv] - \left[\frac{1}{a\cos\varphi}\frac{\partial\Phi}{\partial\lambda}\right] - \left[\frac{1}{a\cos^2\varphi}\frac{\partial(uv\cos^2\varphi)}{\partial\varphi}\right] - \cancel{\left[\frac{1}{a\cos\varphi}\frac{\partial(uu)}{\partial\lambda}\right]} - \cancel{u_s\omega_s} = \tau_u$$

small small

Mountain Torque (M)

Upon taking the zonal mean…

$$[fv] + M - \left[\frac{1}{a\cos^2\varphi}\frac{\partial(uv\cos^2\varphi)}{\partial\varphi}\right] = \tau_u$$

The Vertically Integrated Momentum Balance

$$[fv] - \left[\frac{1}{a\cos\varphi}\frac{\partial\Phi}{\partial\lambda}\right] - \left[\frac{1}{a\cos^2\varphi}\frac{\partial(uv\cos^2\varphi)}{\partial\varphi}\right] - \cancel{\left[\frac{1}{a\cos\varphi}\frac{\partial(uu)}{\partial\lambda}\right]} - \cancel{u_s\omega_s} = \tau_u$$

small

small

Mountain Torque (M)

Upon taking the zonal mean…

$$\boxed{[fv] + M - \left[\frac{1}{a\cos^2\varphi}\frac{\partial(uv\cos^2\varphi)}{\partial\varphi}\right]} = \tau_u$$

Resolved Dynamics Terms

The Vertically Integrated Momentum Balance

$$[fv] - \left[\frac{1}{a\cos\varphi}\frac{\partial\Phi}{\partial\lambda}\right] - \left[\frac{1}{a\cos^2\varphi}\frac{\partial(uv\cos^2\varphi)}{\partial\varphi}\right] - \cancel{\left[\frac{1}{a\cos\varphi}\frac{\partial(uu)}{\partial\lambda}\right]} - \cancel{u_s\omega_s} = \tau_u$$

small

small

Mountain Torque (M)

Upon taking the zonal mean…

$$\boxed{[fv] + M - \left[\frac{1}{a\cos^2\varphi}\frac{\partial(uv\cos^2\varphi)}{\partial\varphi}\right]} = \boxed{\tau_u}$$

Resolved Dynamics Terms

Surface Wind Stress

The Vertically Integrated Momentum Balance

$$[fv] - \left[\frac{1}{acos\varphi}\frac{\partial\Phi}{\partial\lambda}\right] - \left[\frac{1}{ac\ldots}\quad\frac{\partial(uvcos^2\varphi)}{\ldots}\right] \left[\frac{1}{\ldots}\cancel{\frac{\partial(uu)}{\ldots}}\right] \ldots u$$

Mountain Torque (M)

Can we explain the CMIP vs Reanalysis difference in surface wind stress through a difference in the resolved dynamics terms

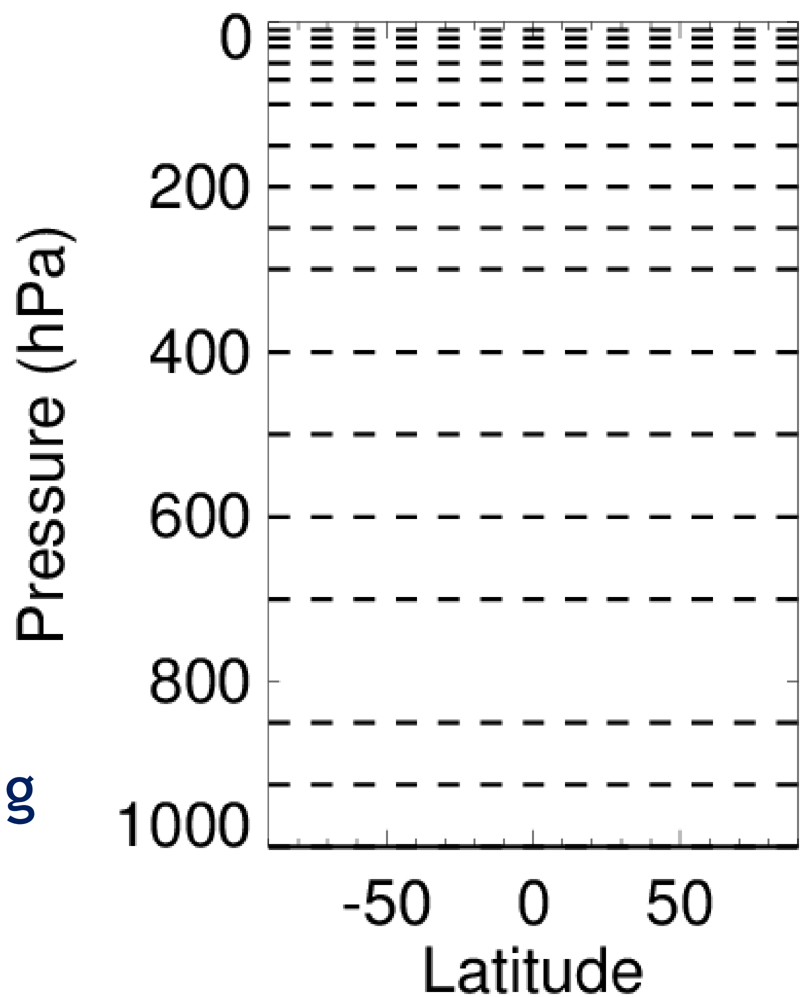
Upon taking the zonal mean…

$$\underbrace{\boxed{[fv] + M - \left[\frac{1}{acos^2\varphi}\frac{\partial(uvcos^2\varphi)}{\partial\varphi}\right]}}_{\text{Resolved Dynamics Terms}} = \underbrace{\boxed{\tau_u}}_{\text{Surface Wind Stress}}$$

Calculated using the 17 standard CMIP5 pressure levels

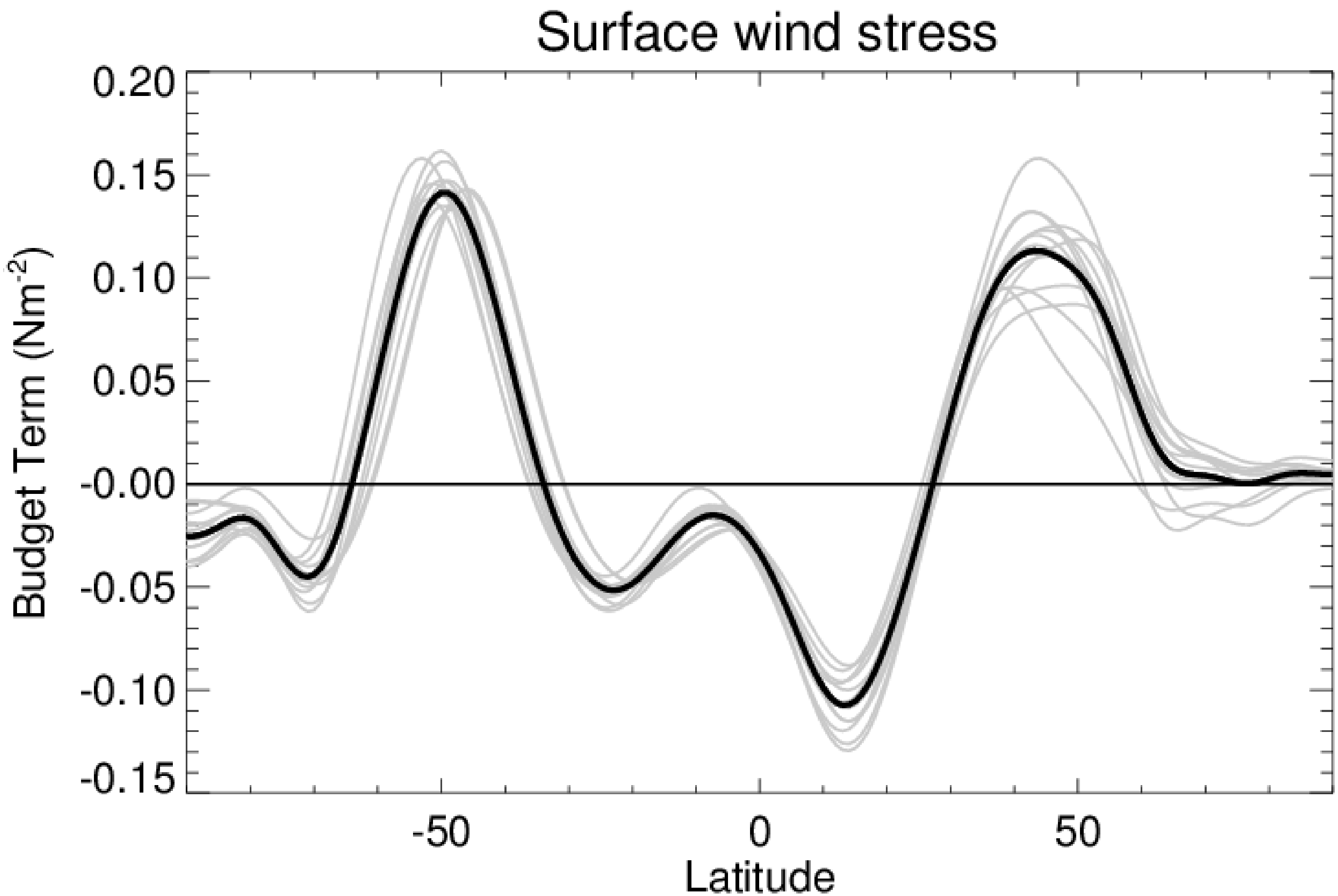
Vertical integral performed on monthly mean fields using monthly mean surface pressure.

Momentum fluxes calculated using 6 hourly instantaneous fields.



Simpson, Shaw and Seager (2014)

The budget closure in the CMIP5 models (DJF)



13 models — Multi-model mean

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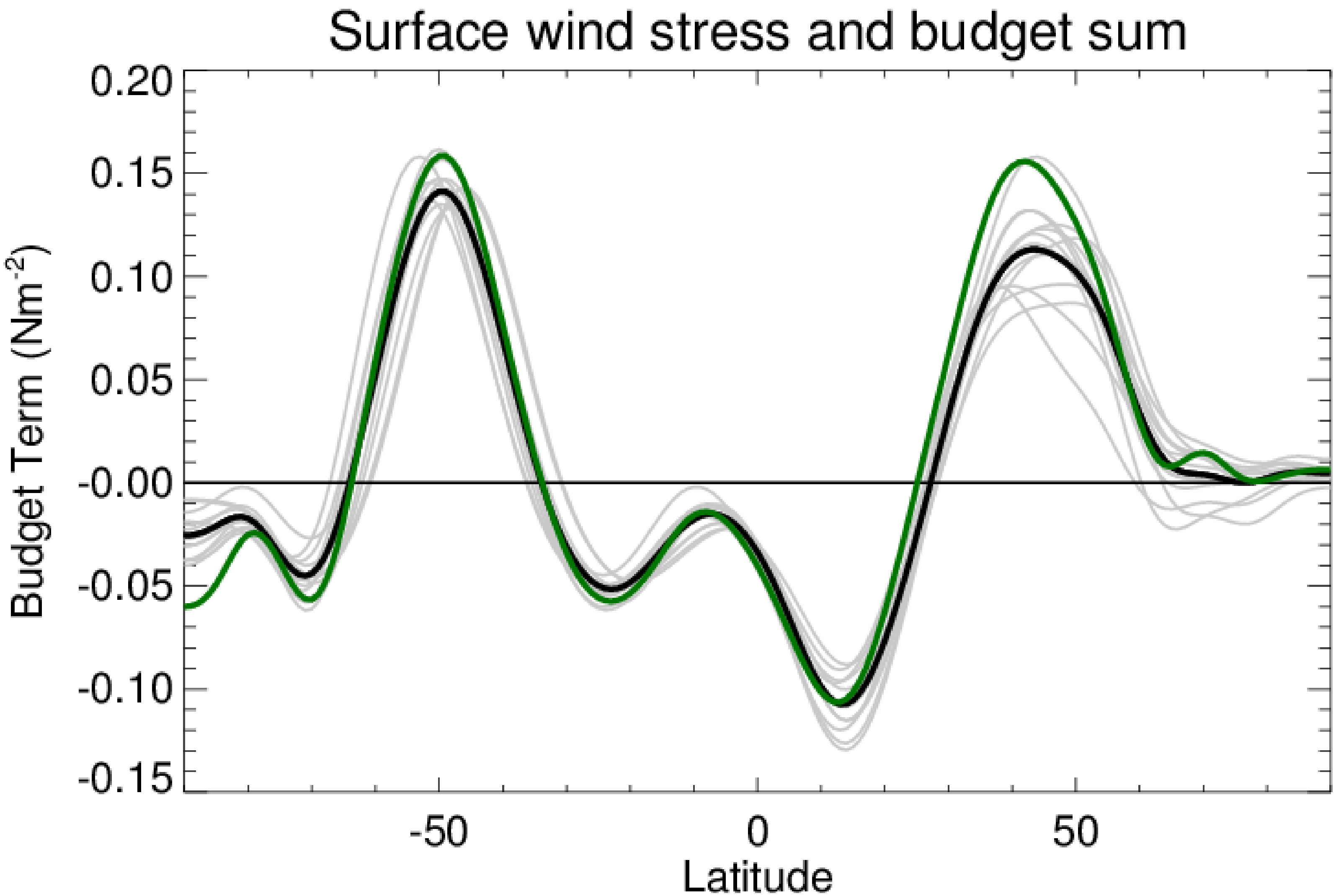

13 models　Multi-model mean　Resolved Dynamics Tendencies

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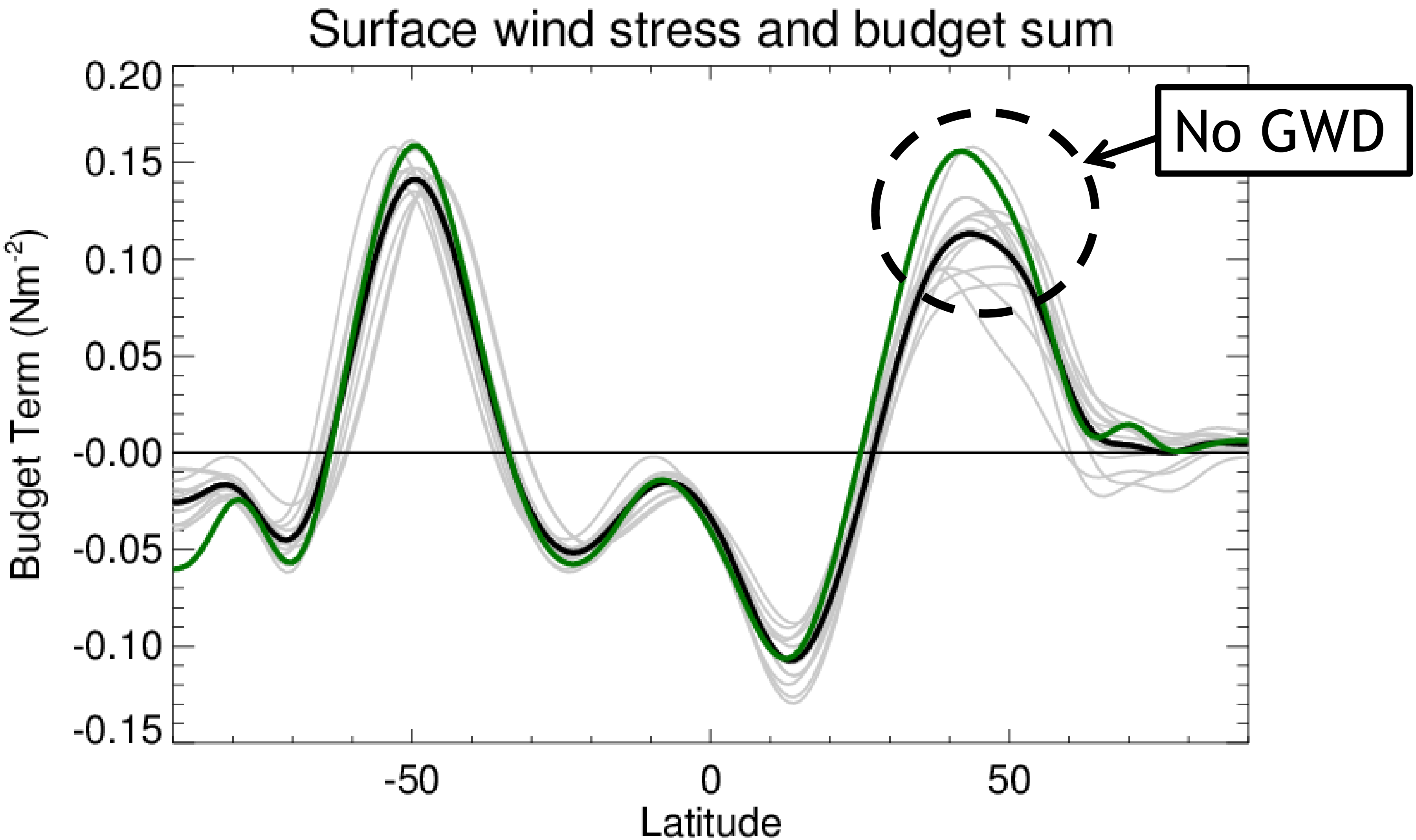

13 models — Multi-model mean — Resolved Dynamics Tendencies

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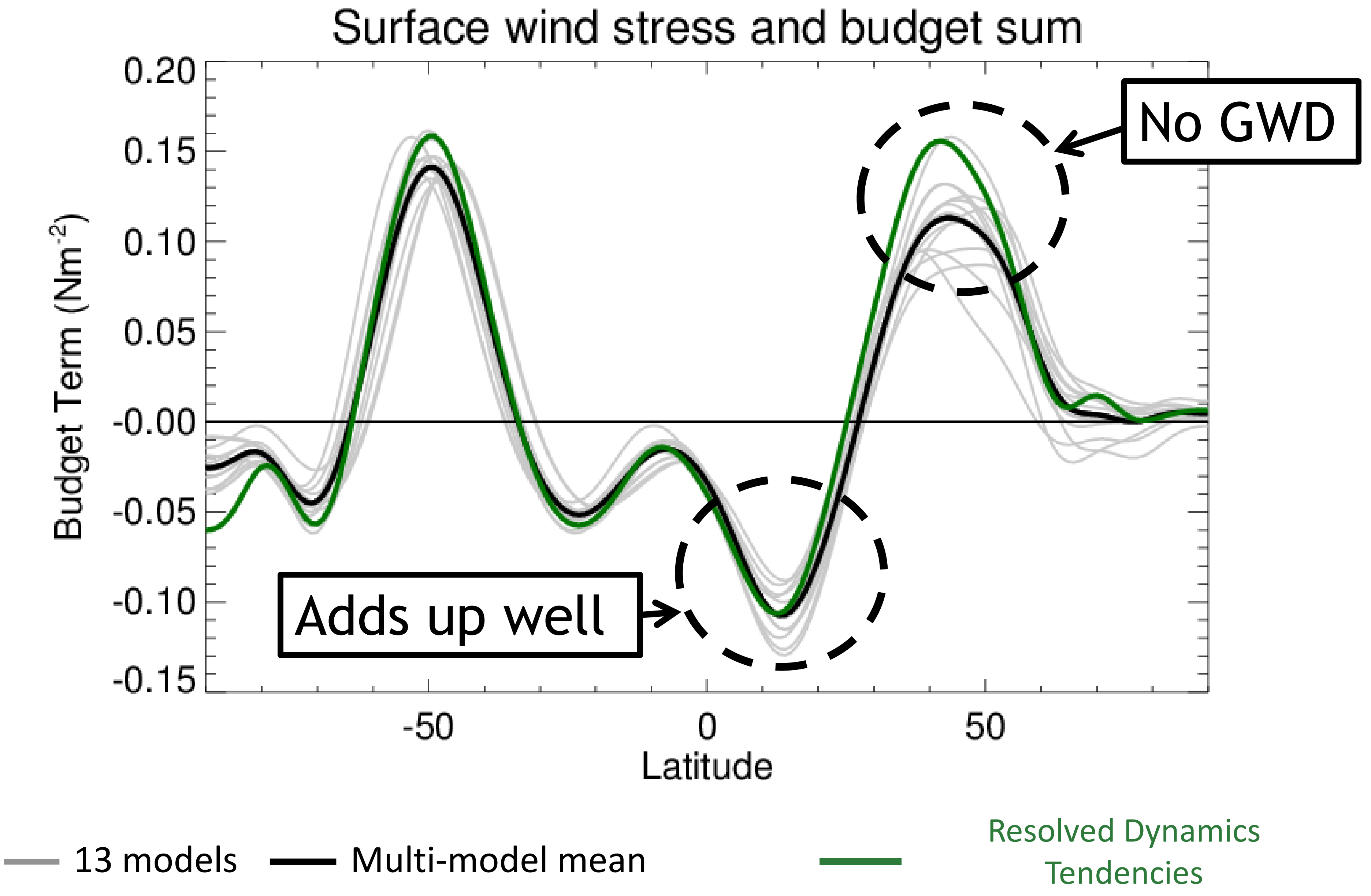
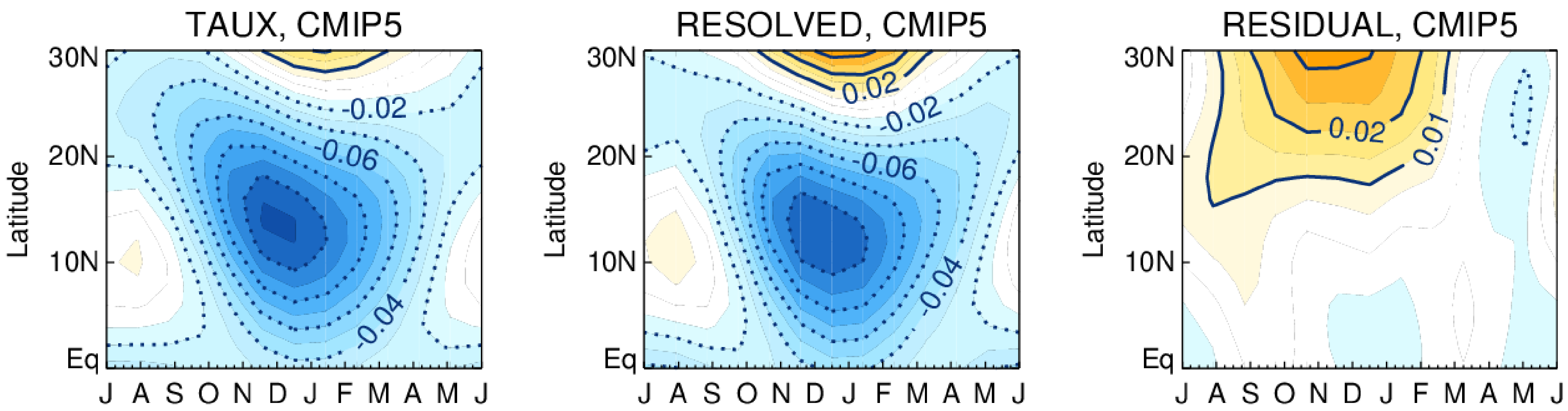


CMIP5 momentum budget as a function of season



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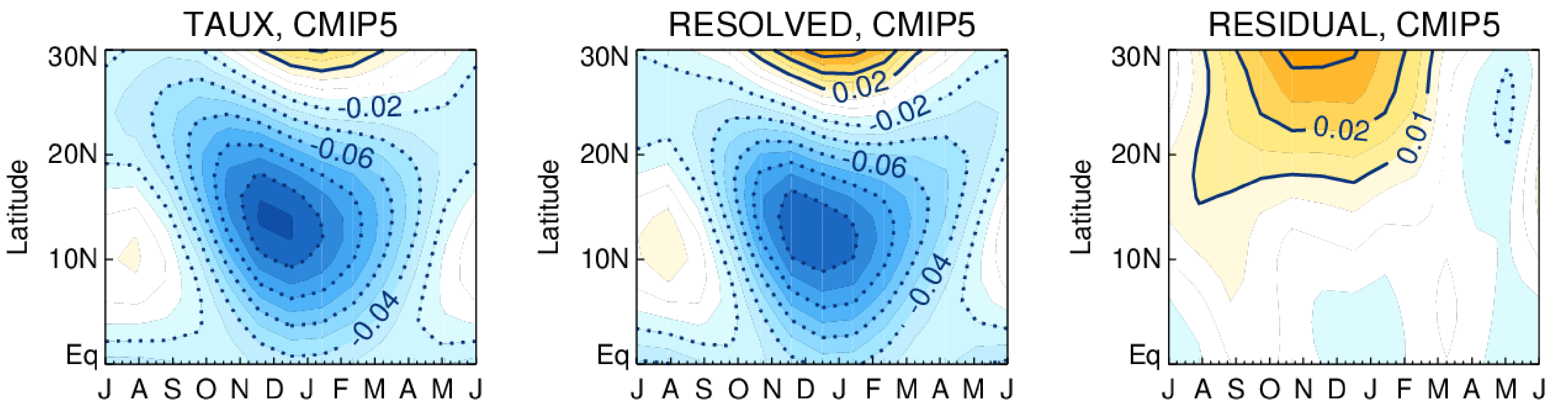
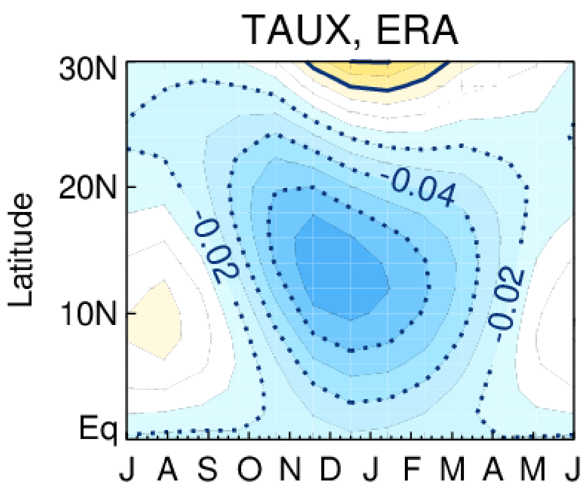


ERA-Interim Budget



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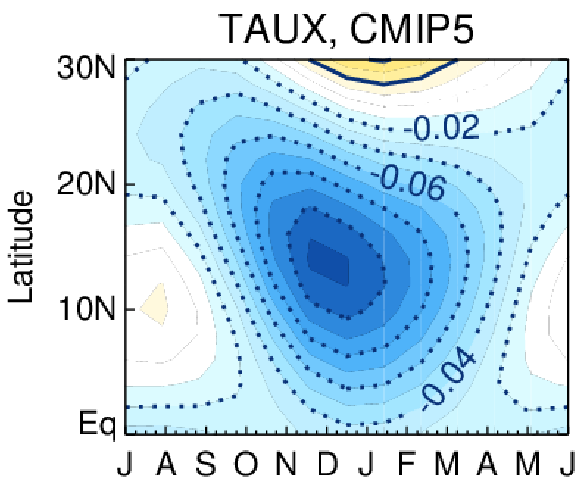

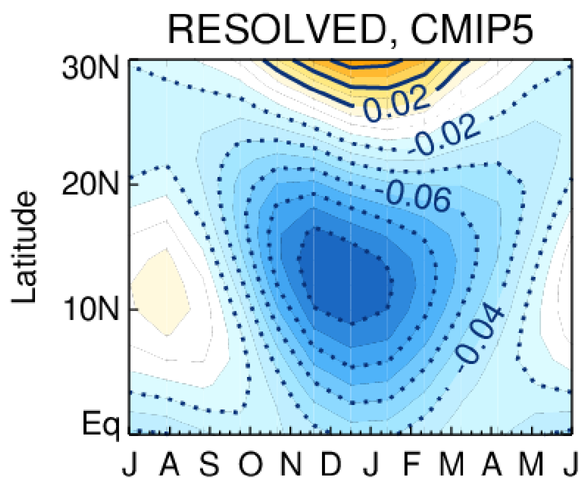

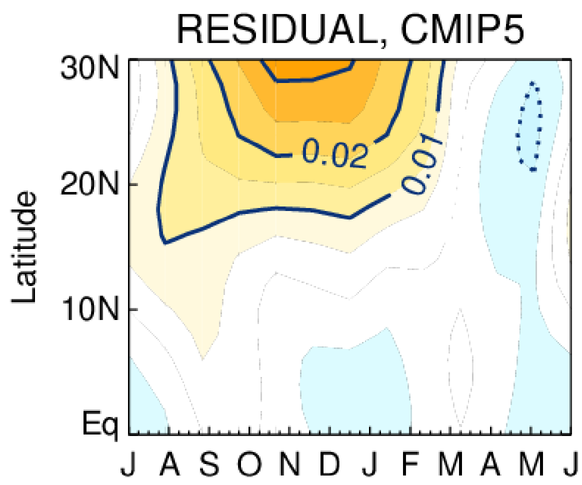

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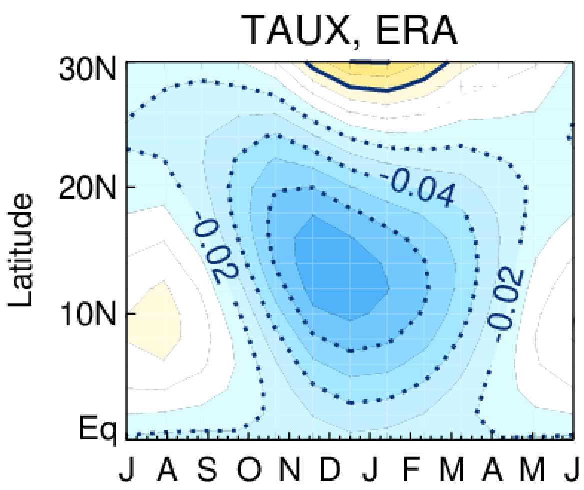
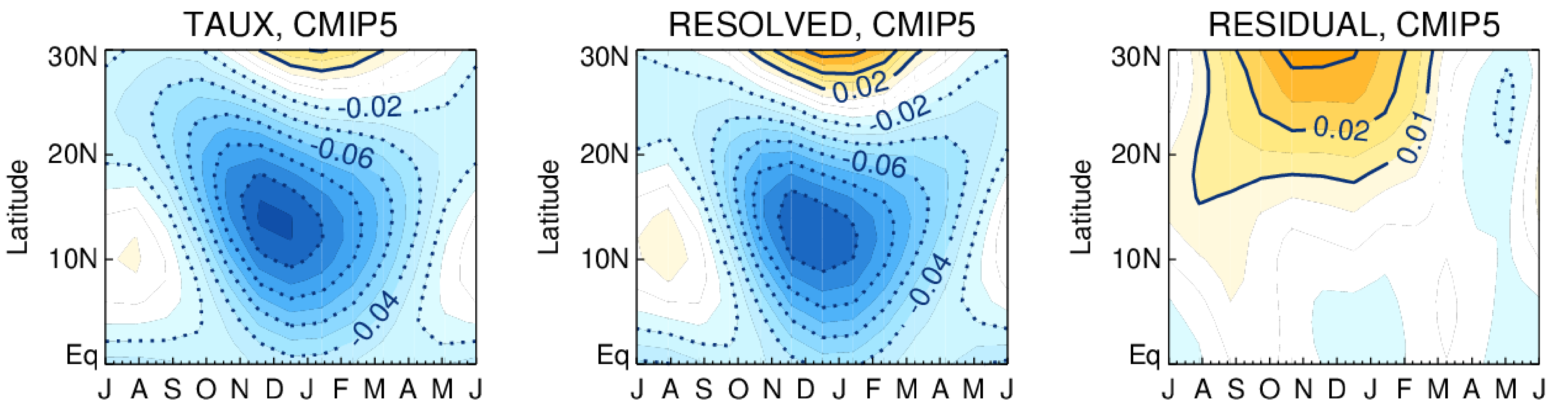


Does the surface wind stress differ because the vertically integrated tendency from the large scale circulation differs?

CMIP5 momentum budget as a function of season



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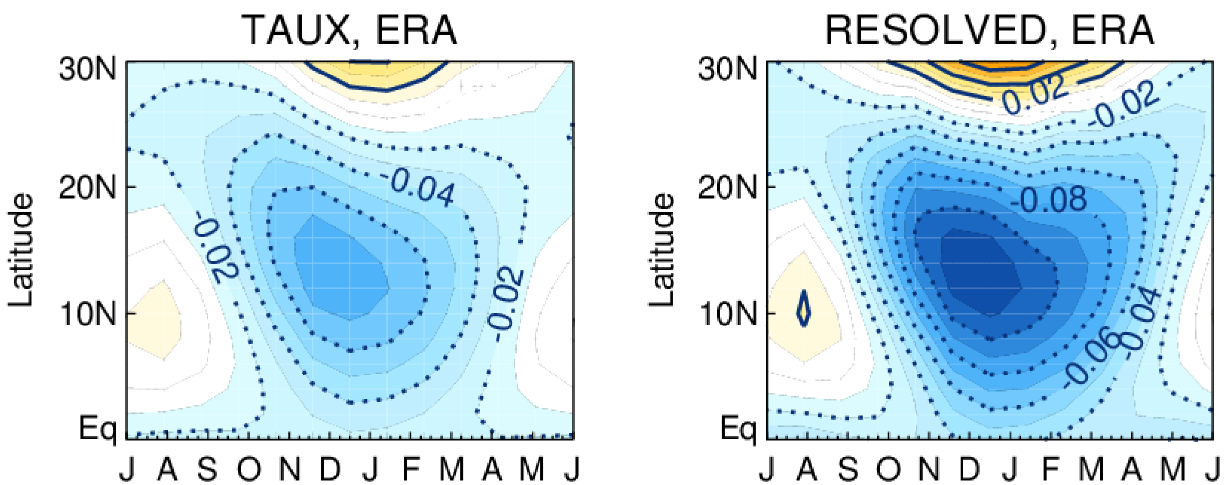

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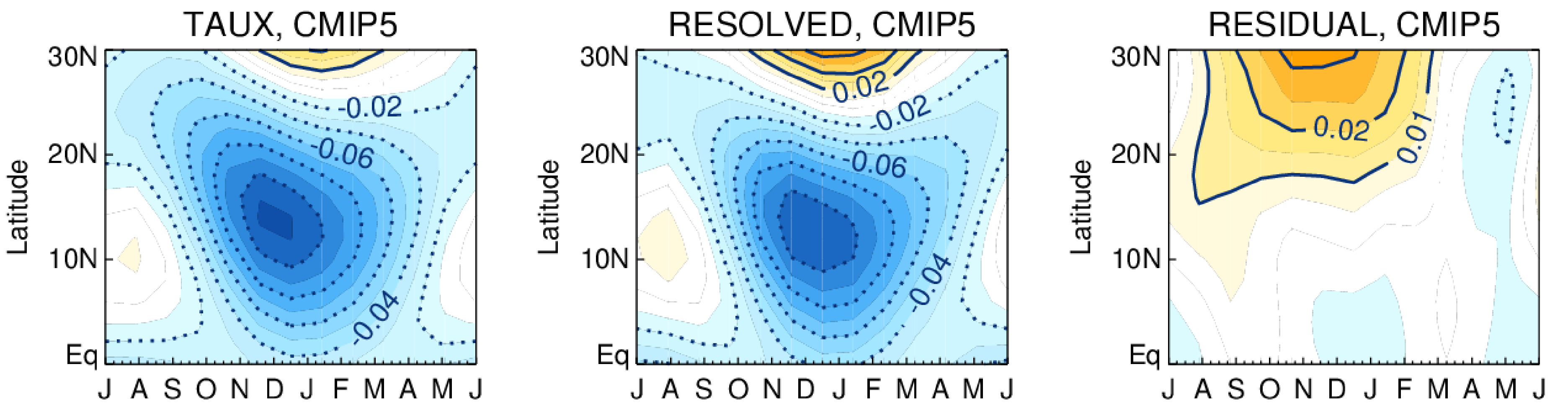

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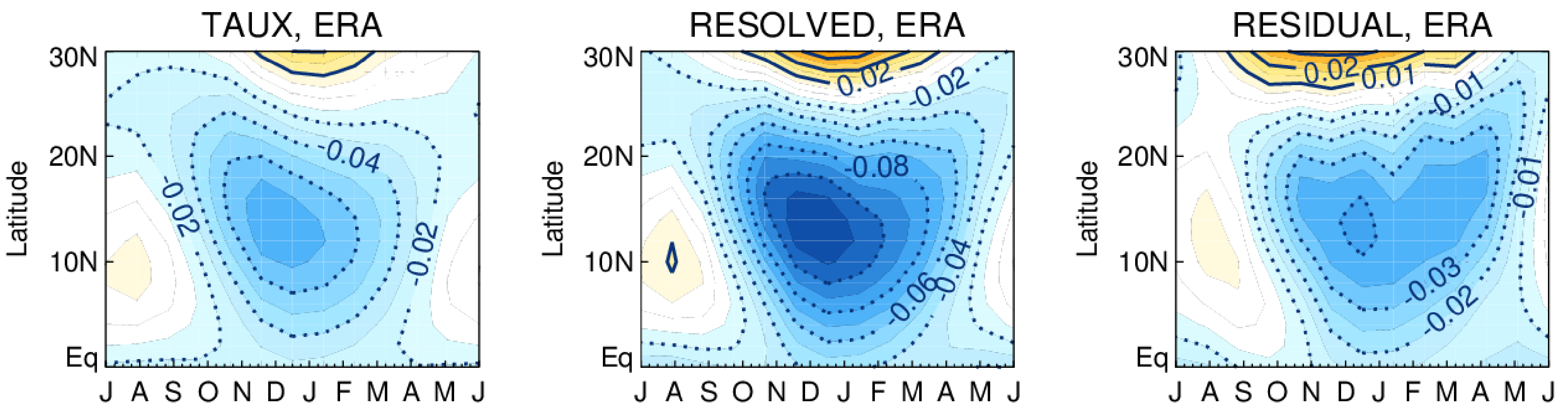

We can't attribute the difference in surface wind stress to a difference in the resolved dynamics terms

Resolved Dynamics

=

Surface wind stress

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Resolved Dynamics

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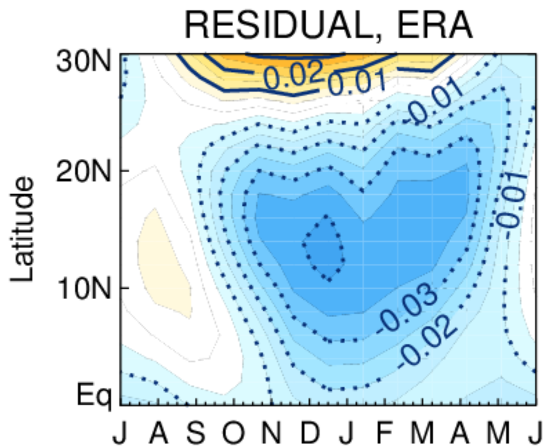
Surface wind stress

Why the residual in ERA-Interim?



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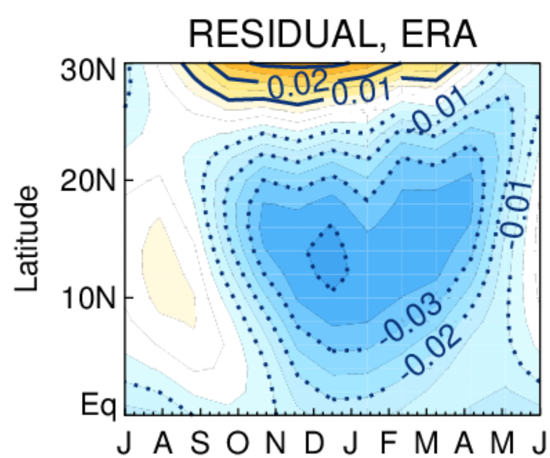

Resolved Dynamics

+

Other parameterized tendencies

+

-dU/dt

=

Surface wind stress

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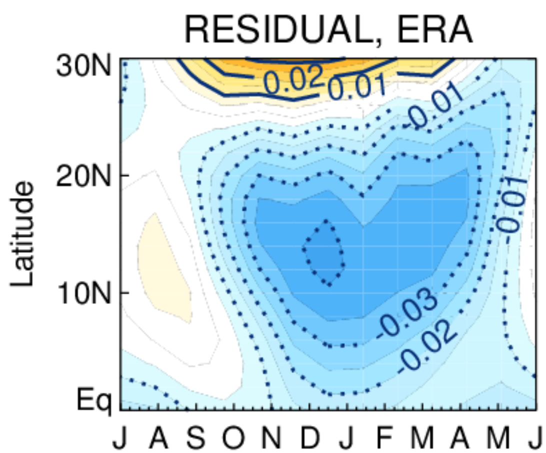

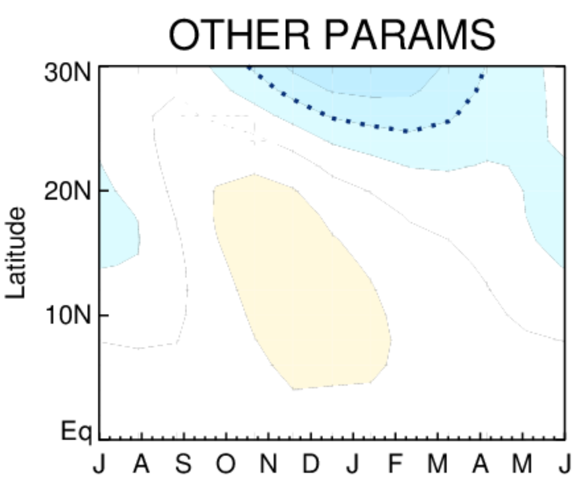

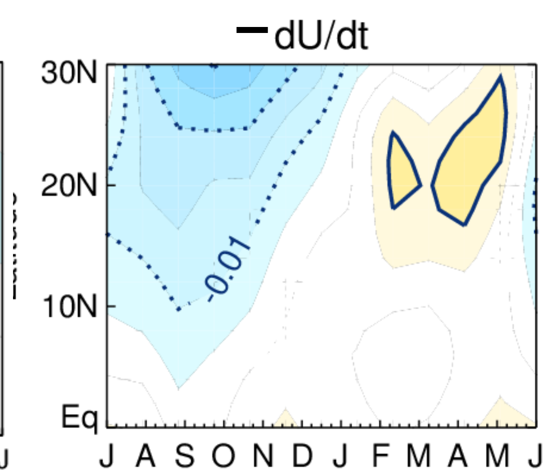

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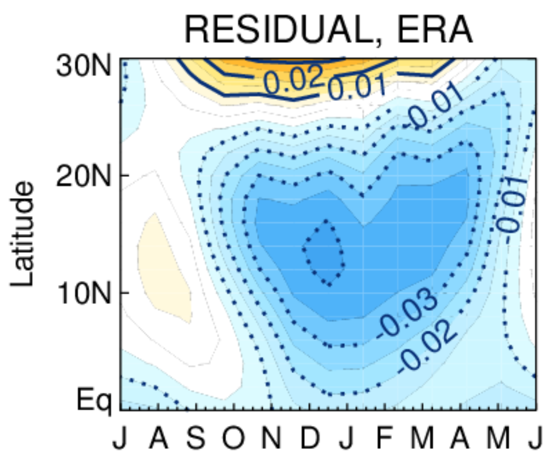

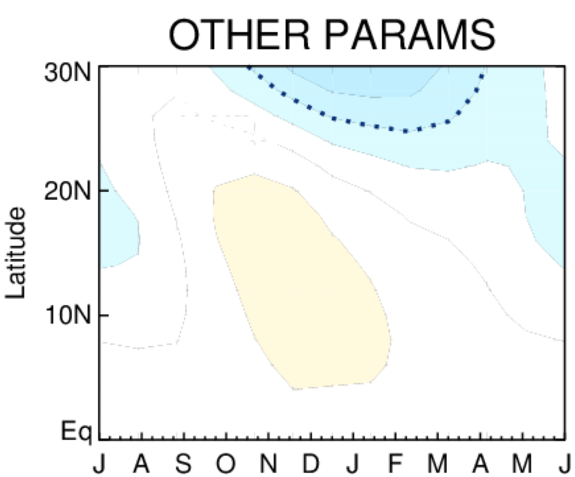

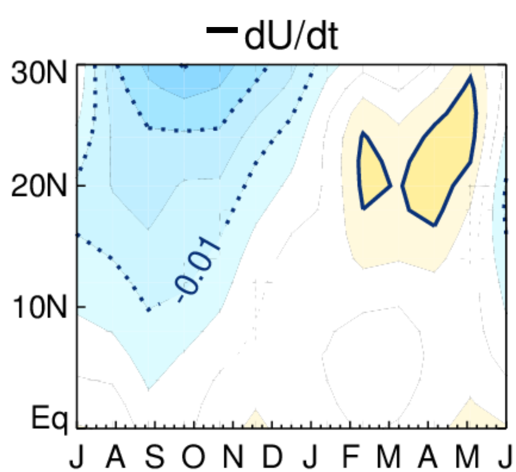

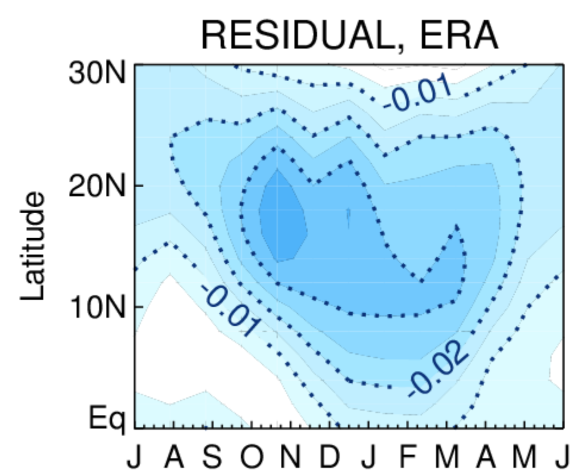

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Resolved Dynamics

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Other parameterized tendencies

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-dU/dt

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Surface wind stress

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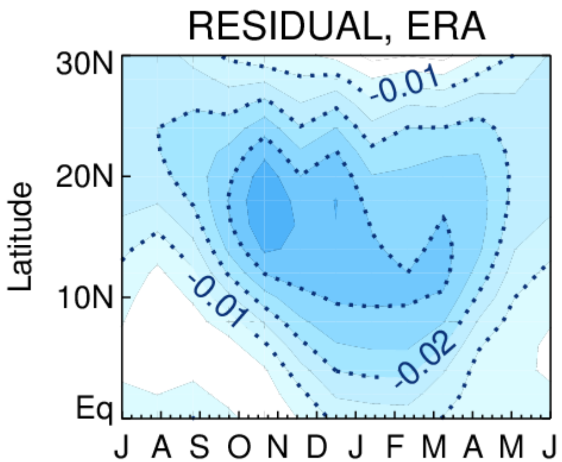

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Surface wind stress

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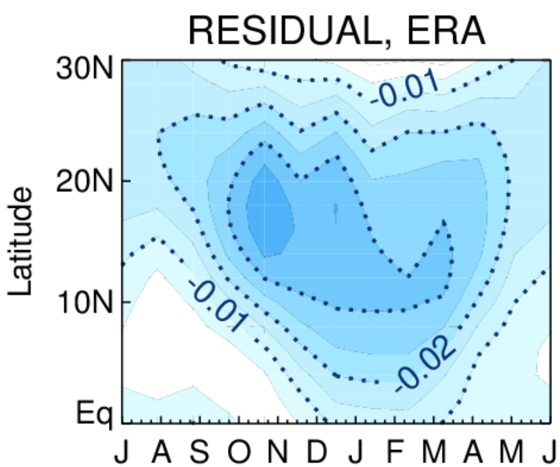
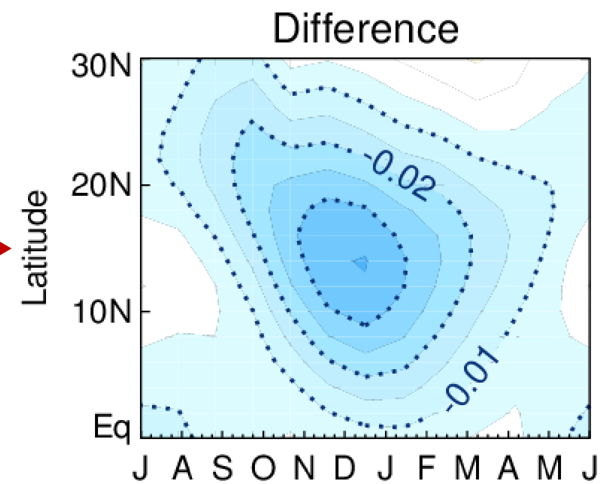


CMIP5 – ERA Interim difference in surface wind stress.



We can't attribute the difference in surface wind stress to a difference in the resolved dynamics terms

Resolved Dynamics

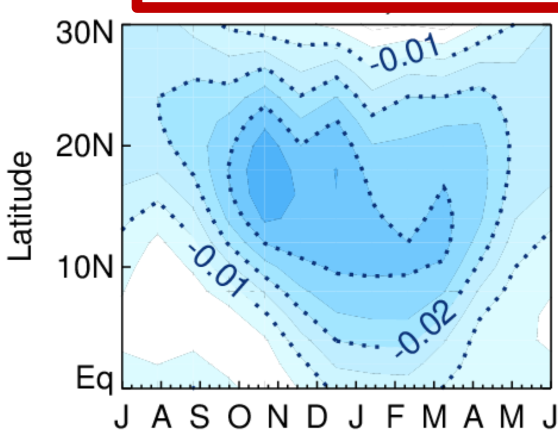
+

Other parameterized tendencies

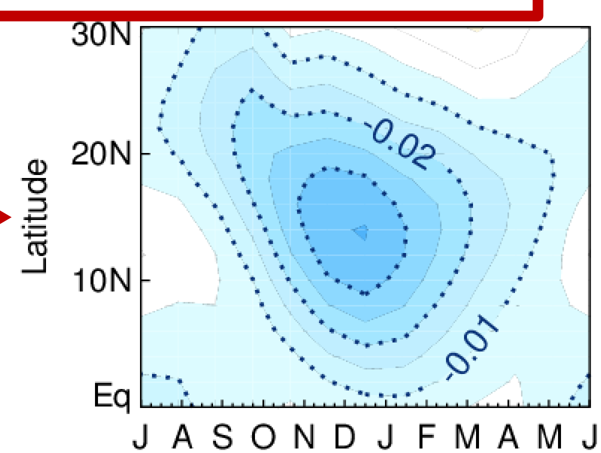
+

Why the residual
in E

We can't explain the difference in surface wind stress between the CMIP5 models and the reanalysis with any of the terms in the vertically integrated budget. The budget doesn't add up in ERA-Interim



CMIP5 – ERA Interim difference in surface wind stress.



We can't attribute the difference in surface wind stress to a difference in the resolved dynamics terms

Why the residual in ERA-Interim?

Resolved Dynamics

\+

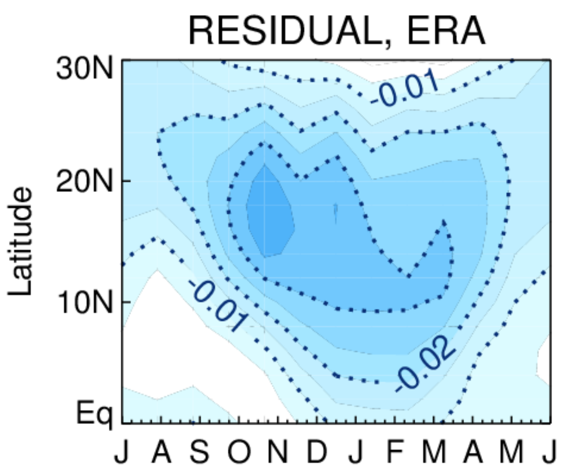
Other parameterized tendencies

\+

-dU/dt

=

Surface wind stress



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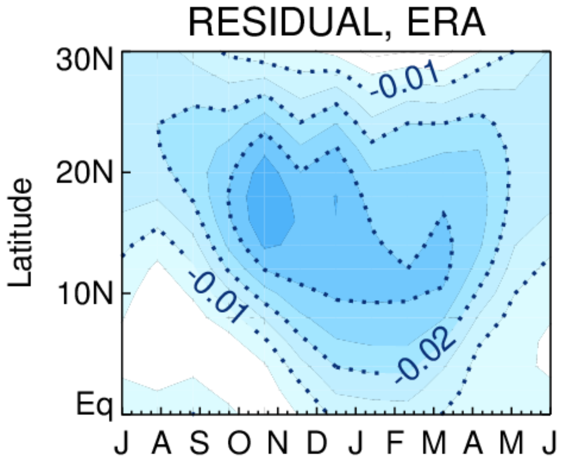


Resolved Dynamics

+

Other parameterized tendencies

+

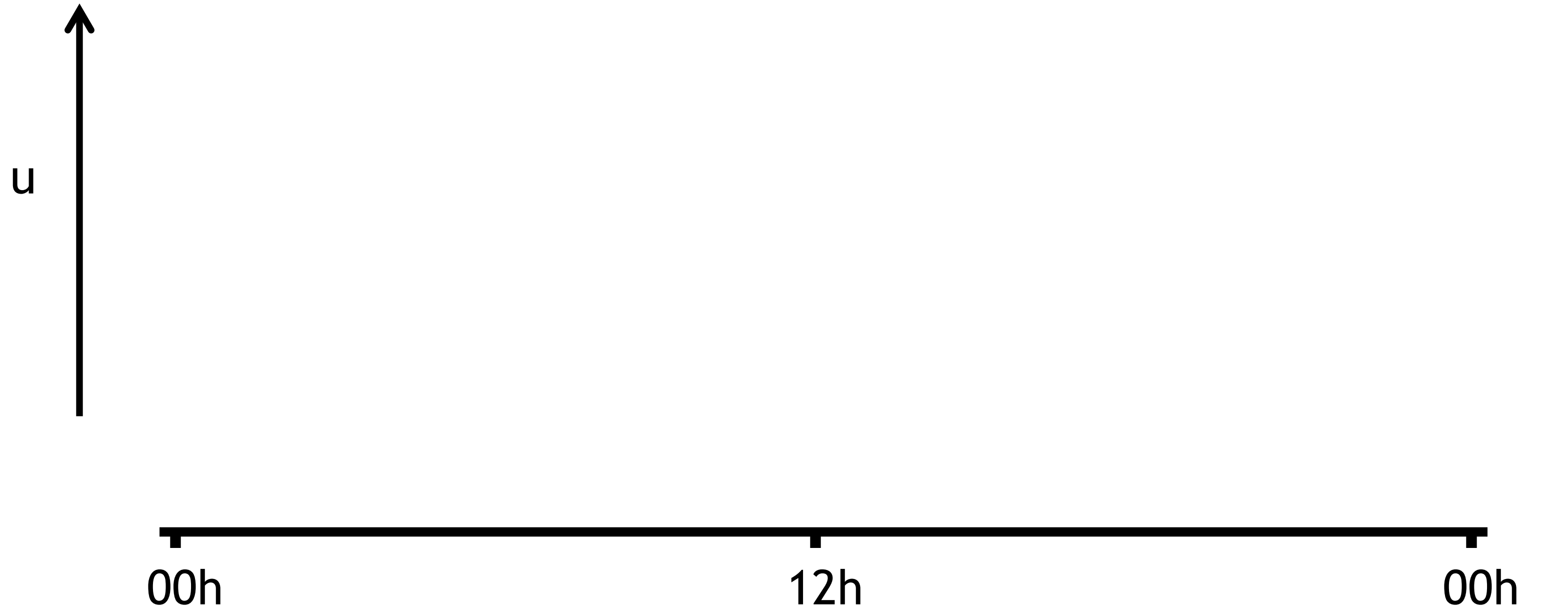
-dU/dt

+

Analysis Increments

=

Surface wind stress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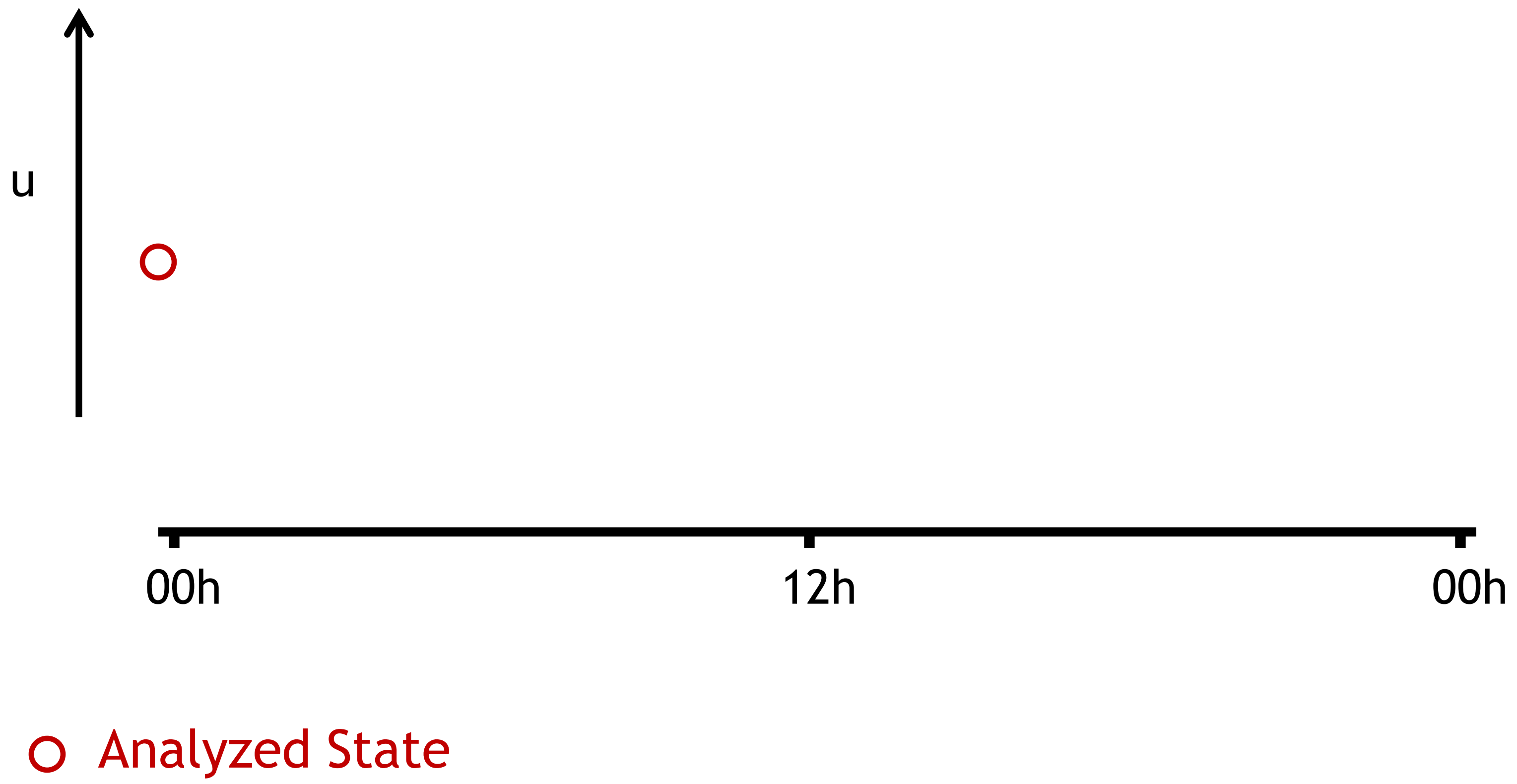
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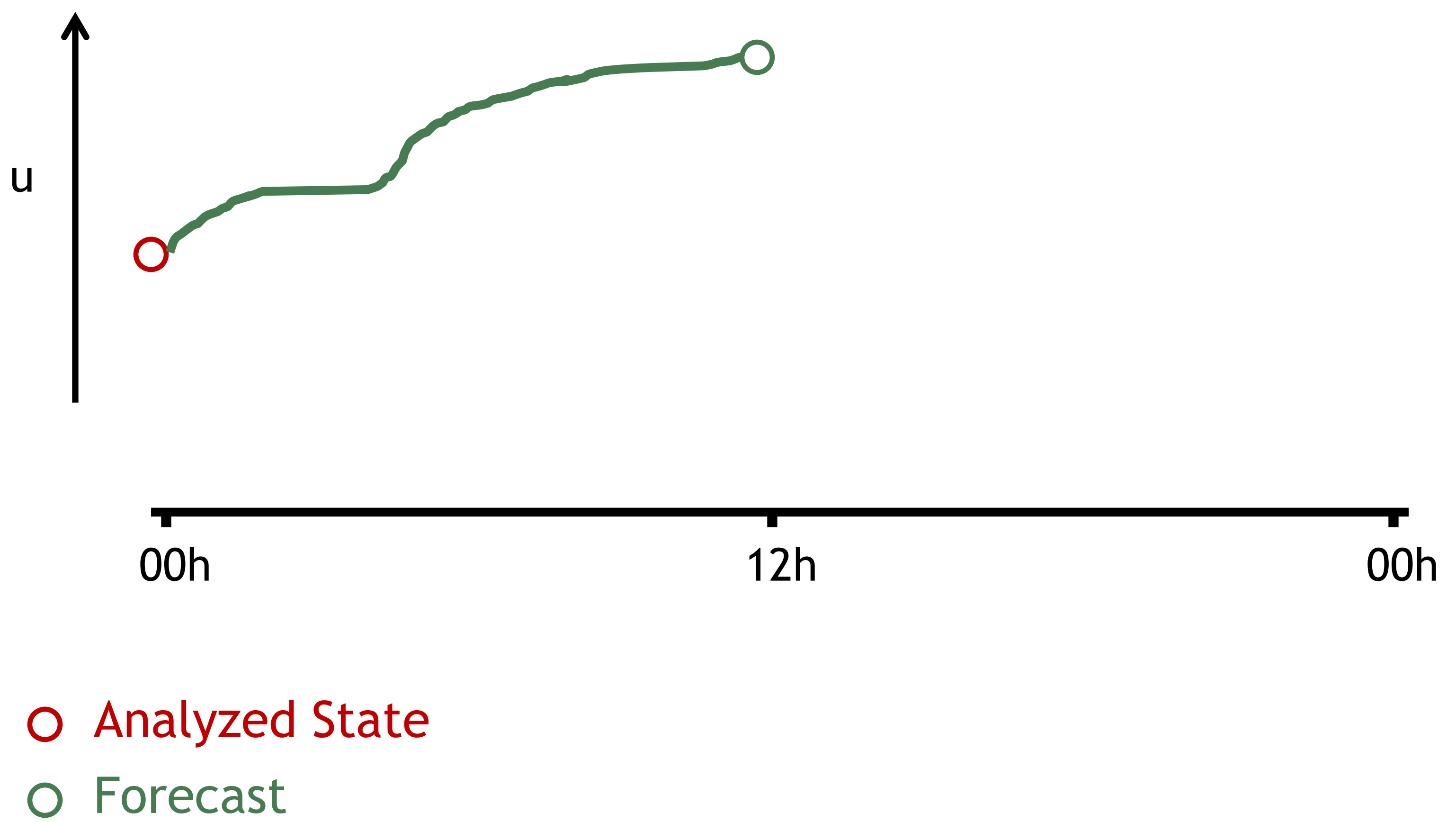
Analyzed State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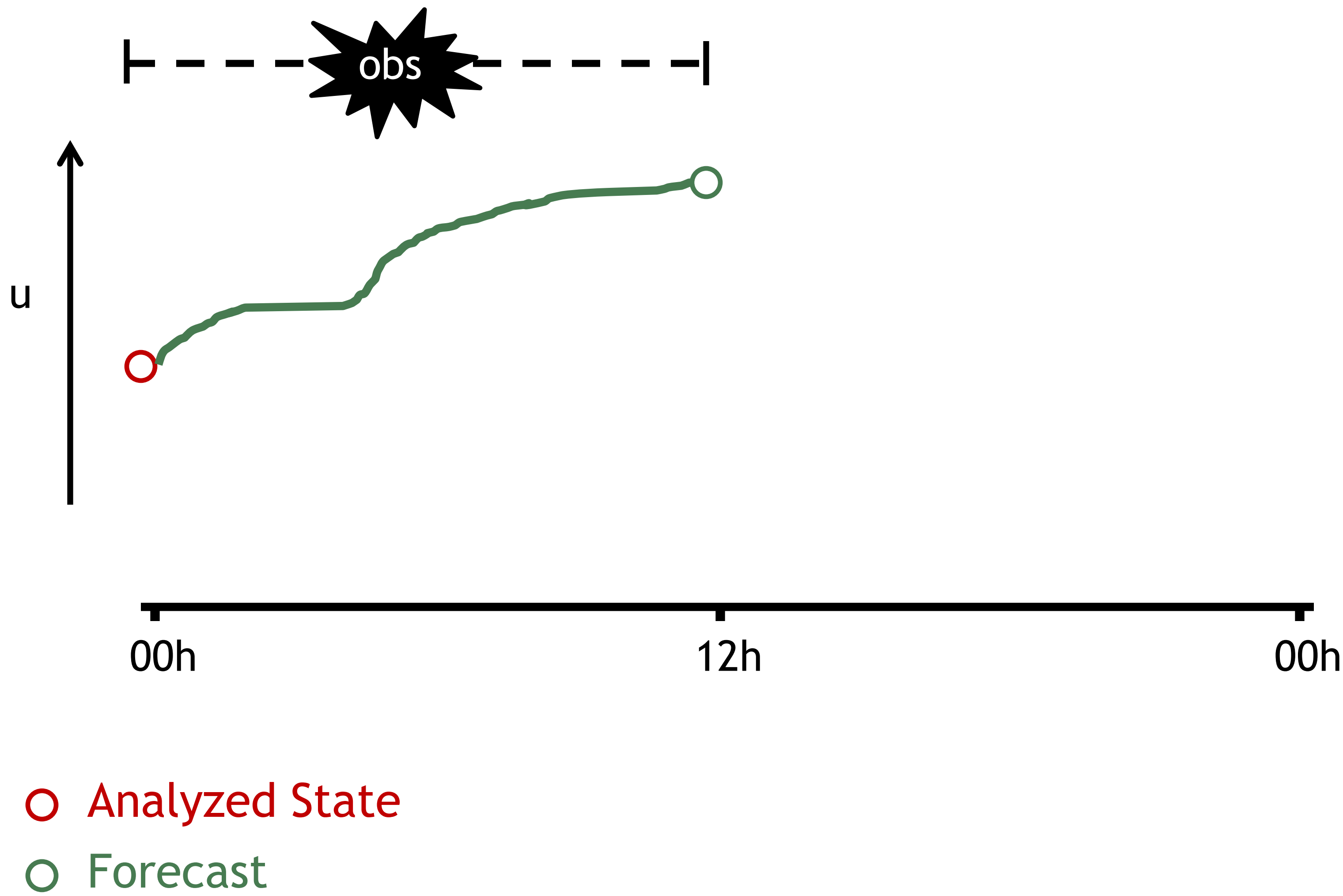
Forecast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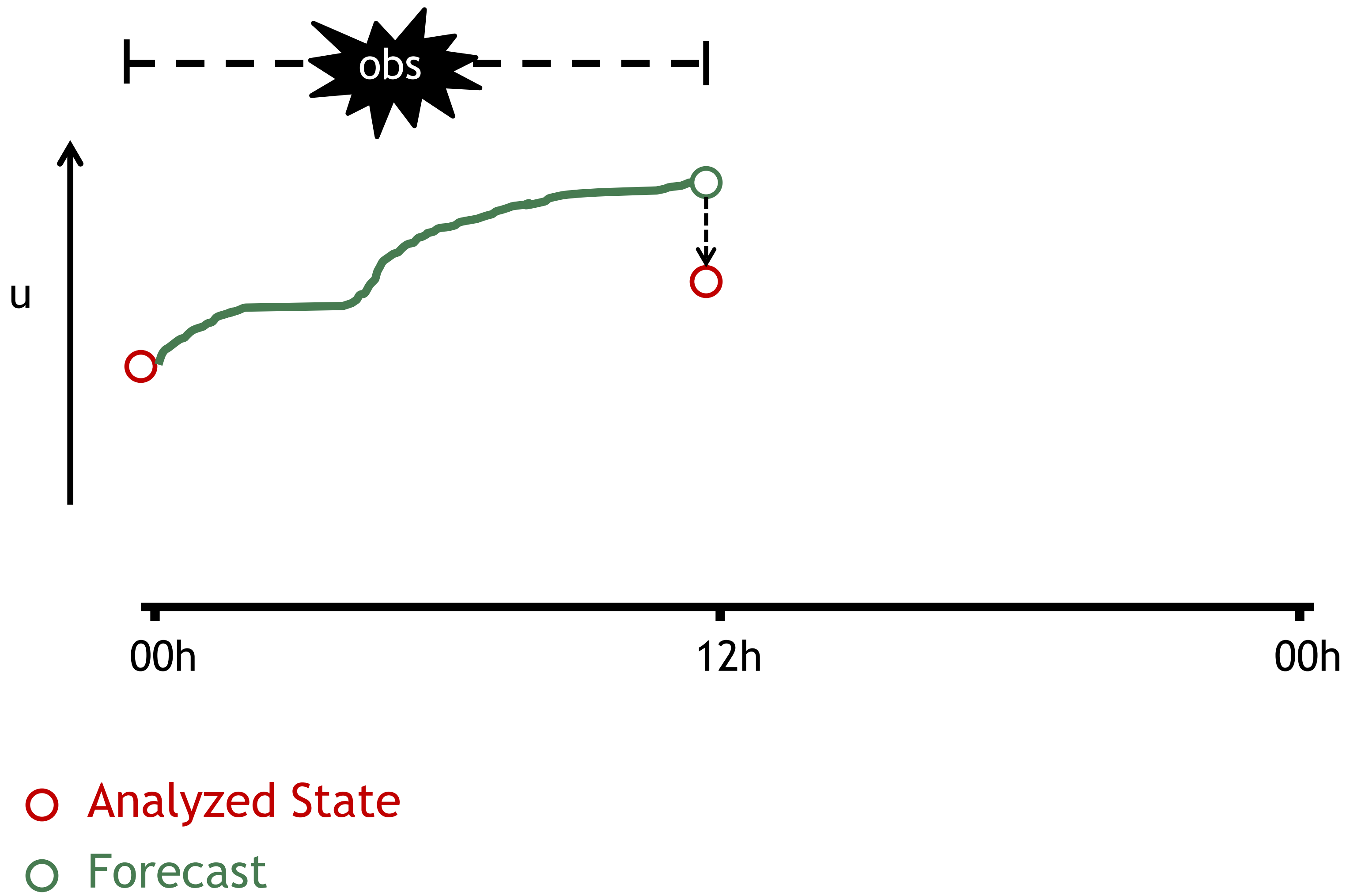
Analyzed State
Forecast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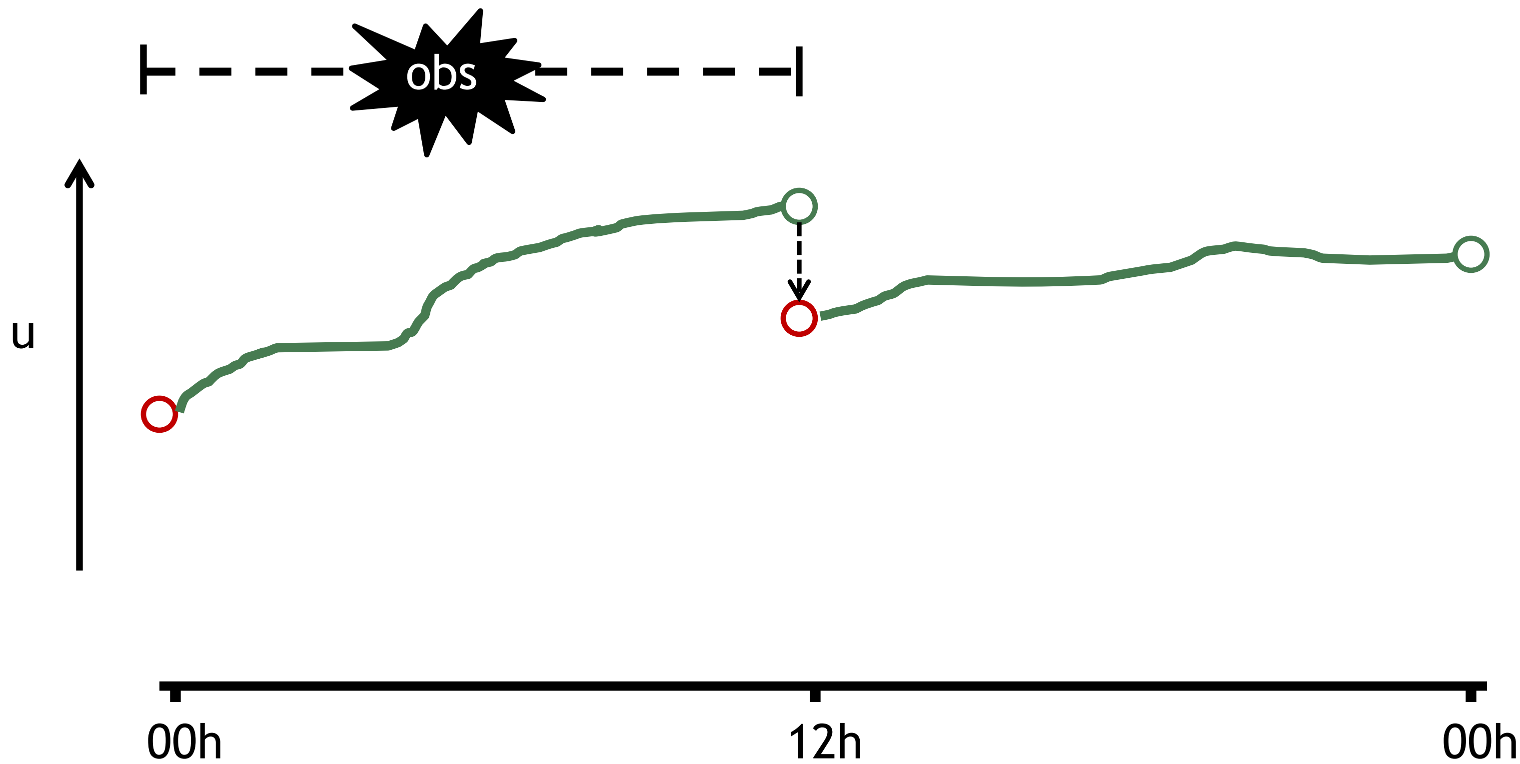
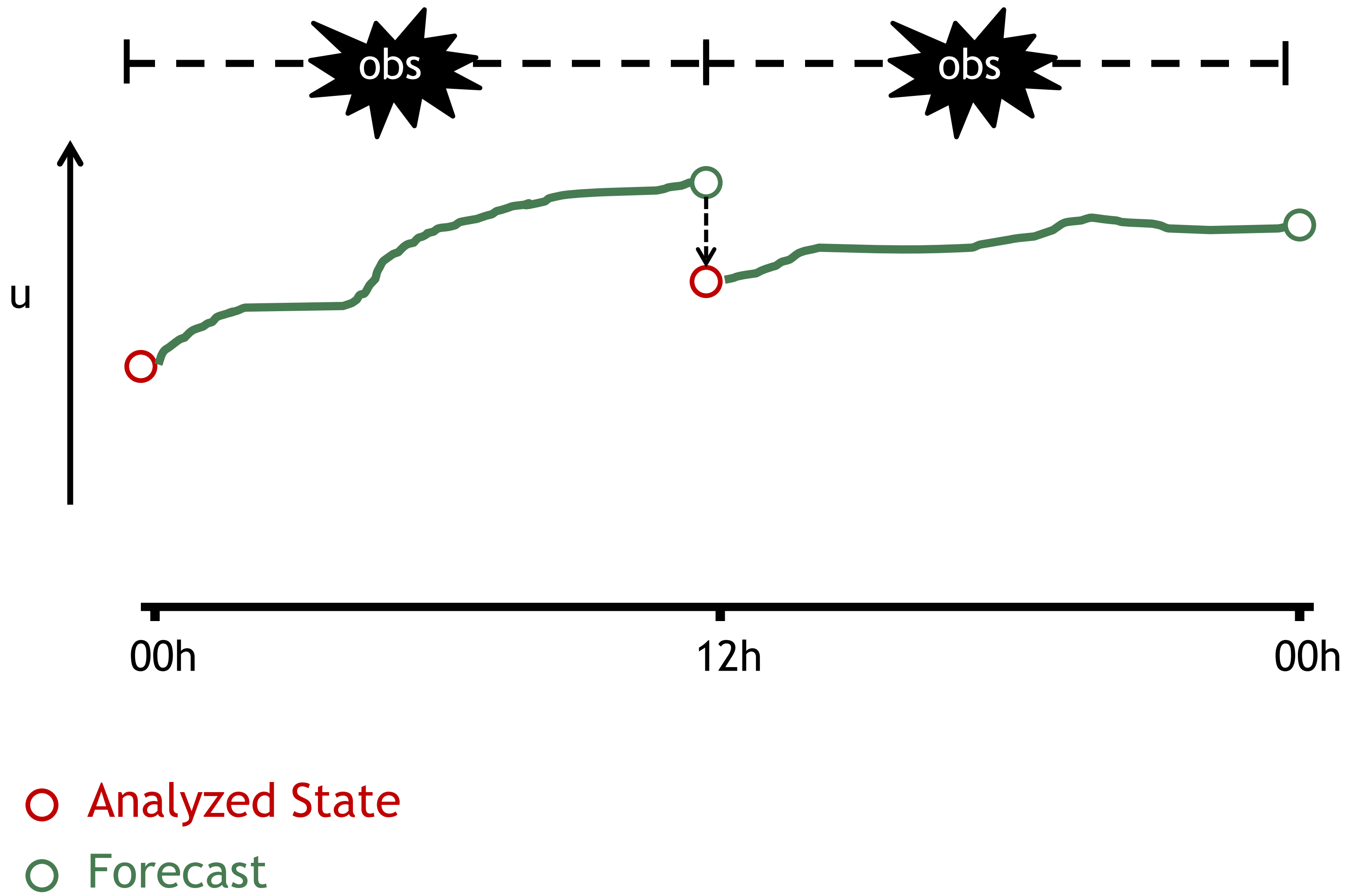


Analyzed State

Forecast



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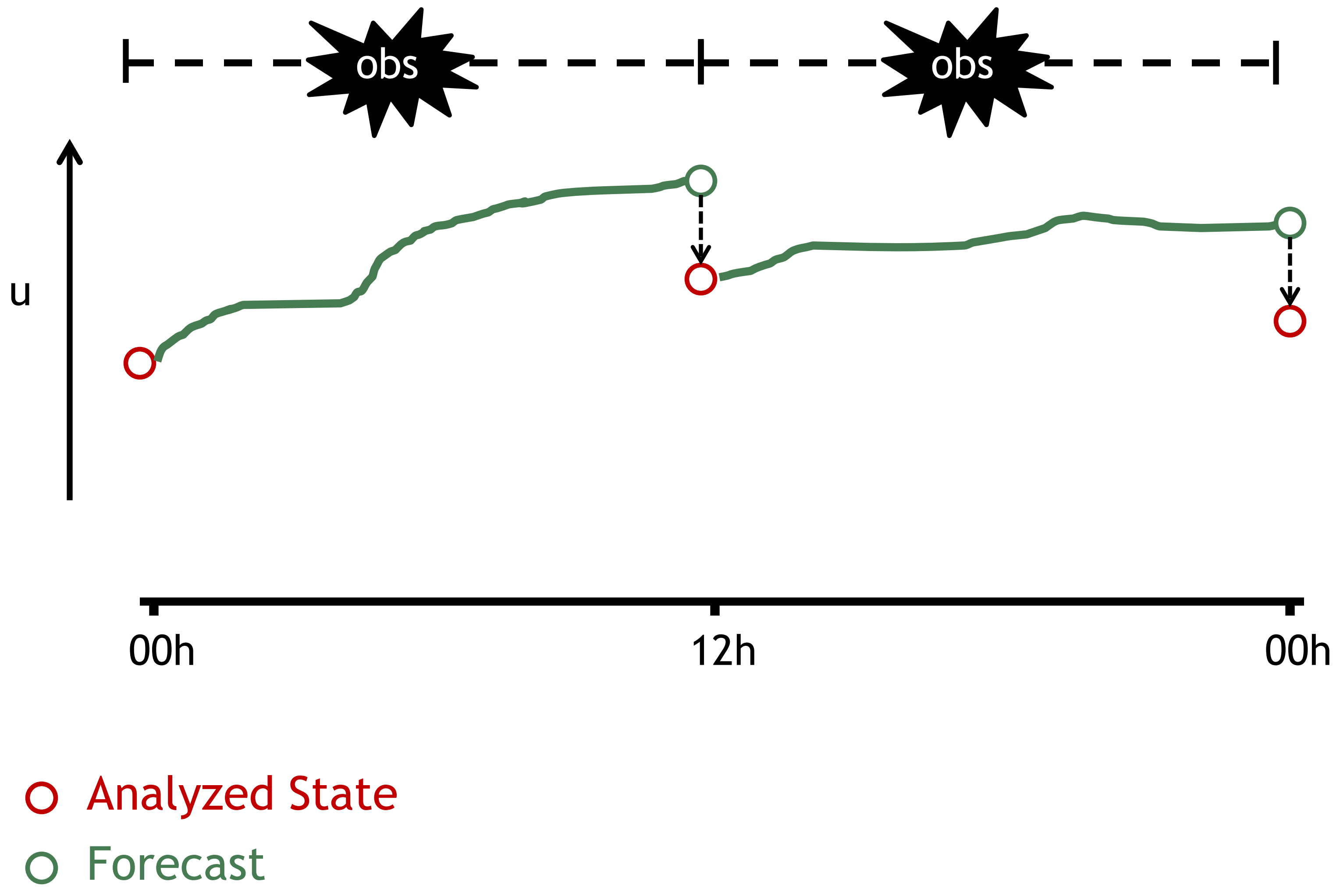
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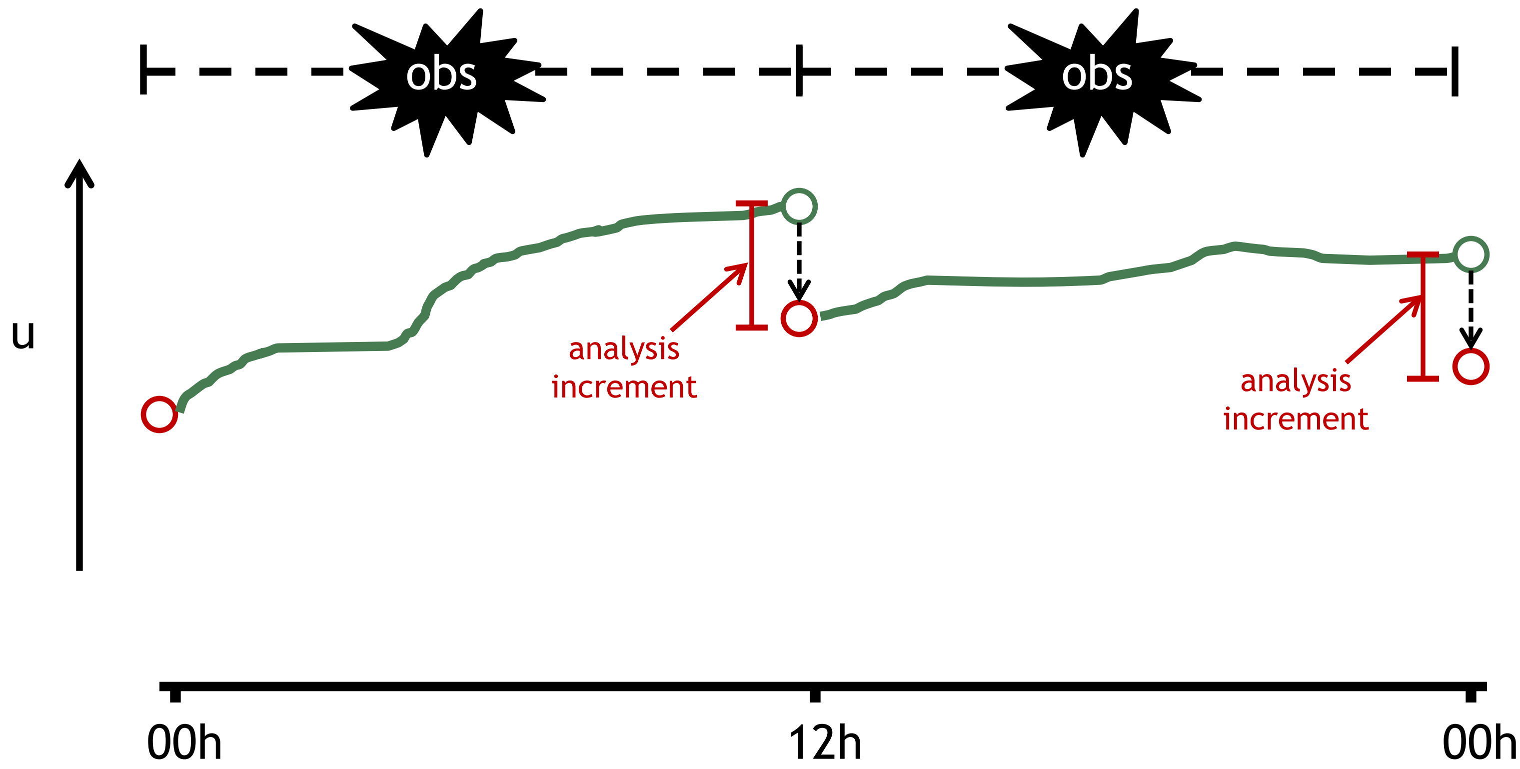
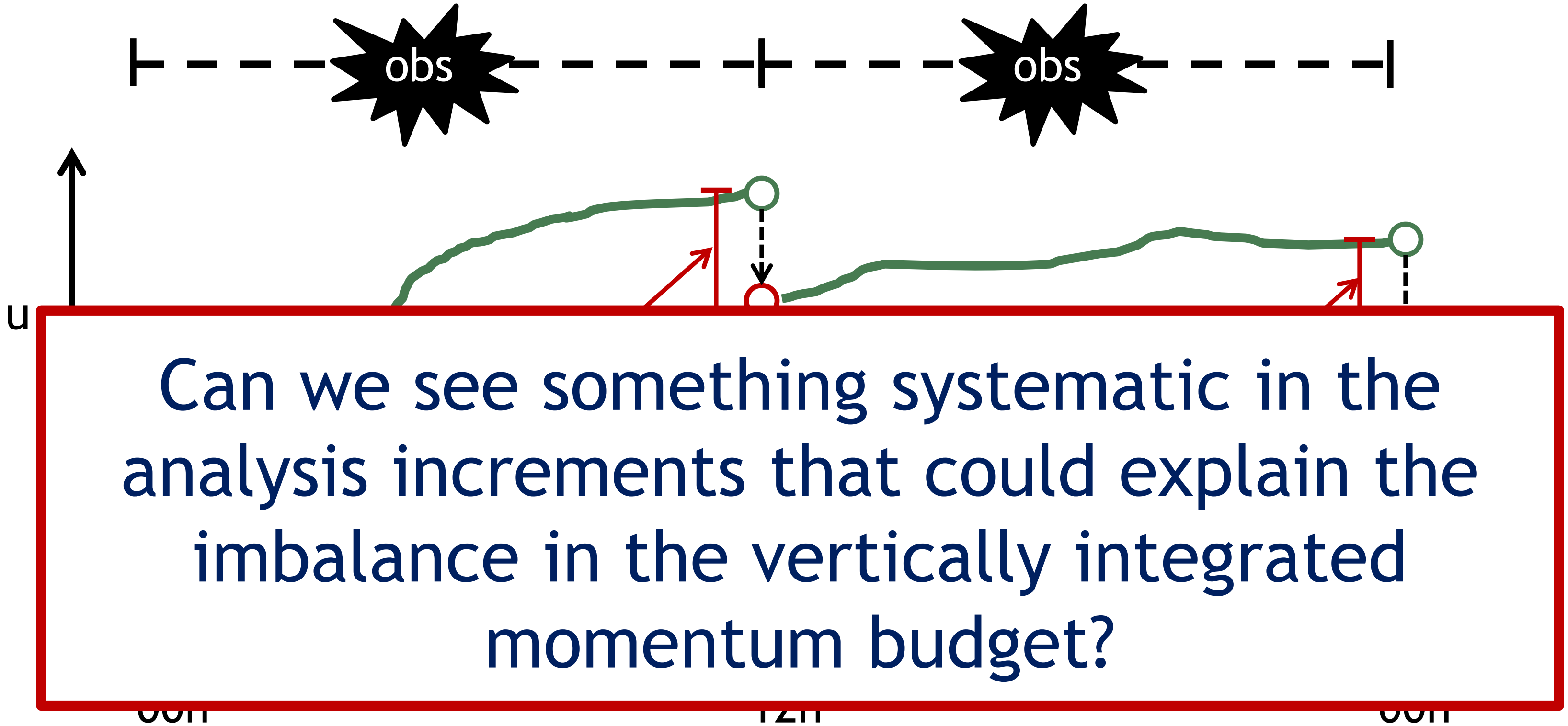


Analyzed State

Forecast

Analysis Increment = Analyzed State - Forecast



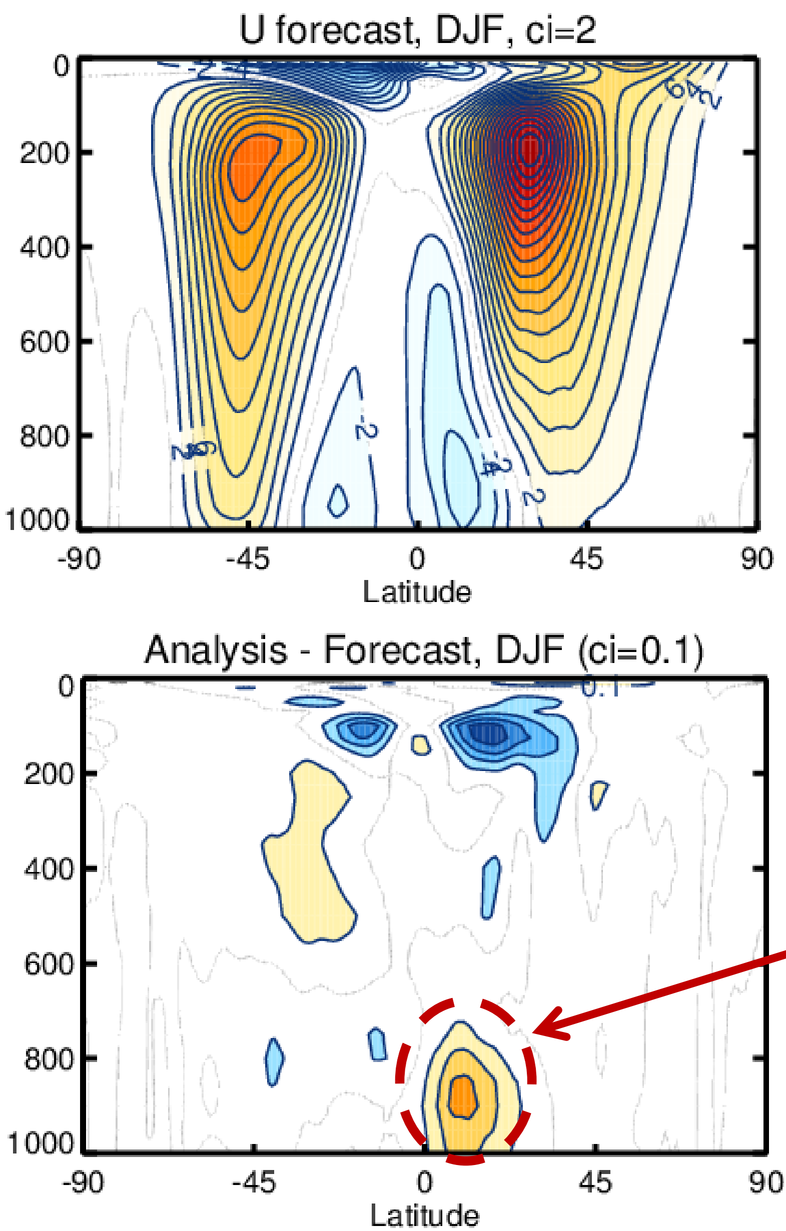
Can we see something systematic in the analysis increments that could explain the imbalance in the vertically integrated momentum budget?

○ Analyzed State

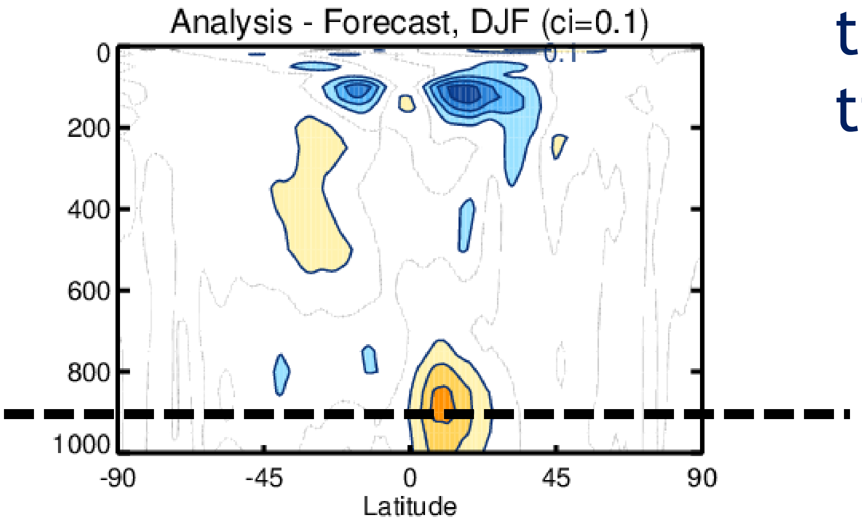
○ Forecast

Analysis Increment = Analyzed State - Forecast

DJF analysis increments

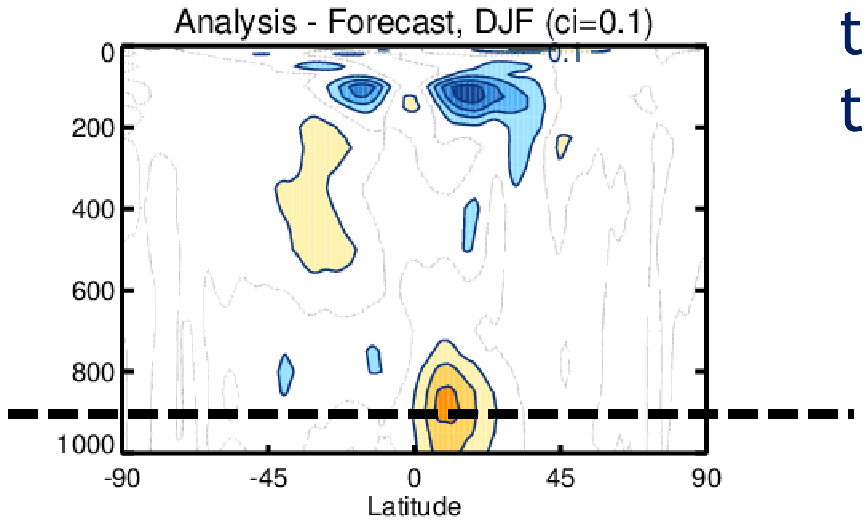


Assimilation acts to reduce the near surface easterly winds



Are these increments present throughout the full 1979-2012 time period?

900hPa zonal mean zonal wind



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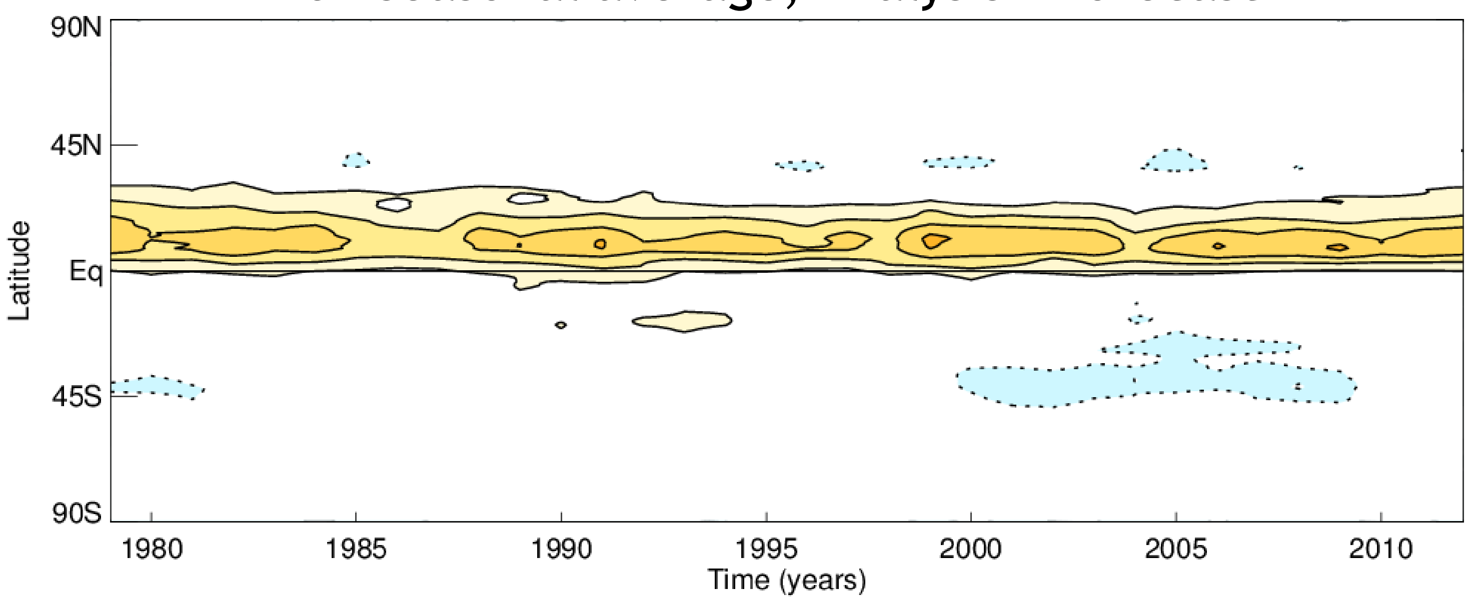
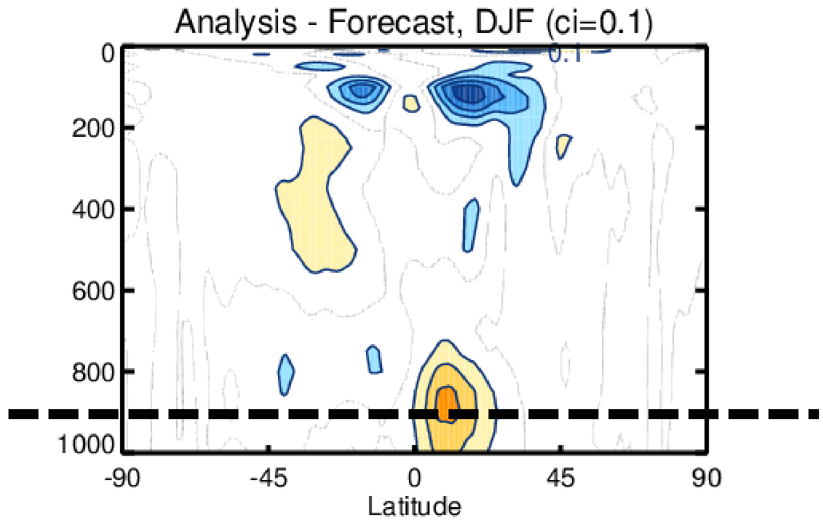
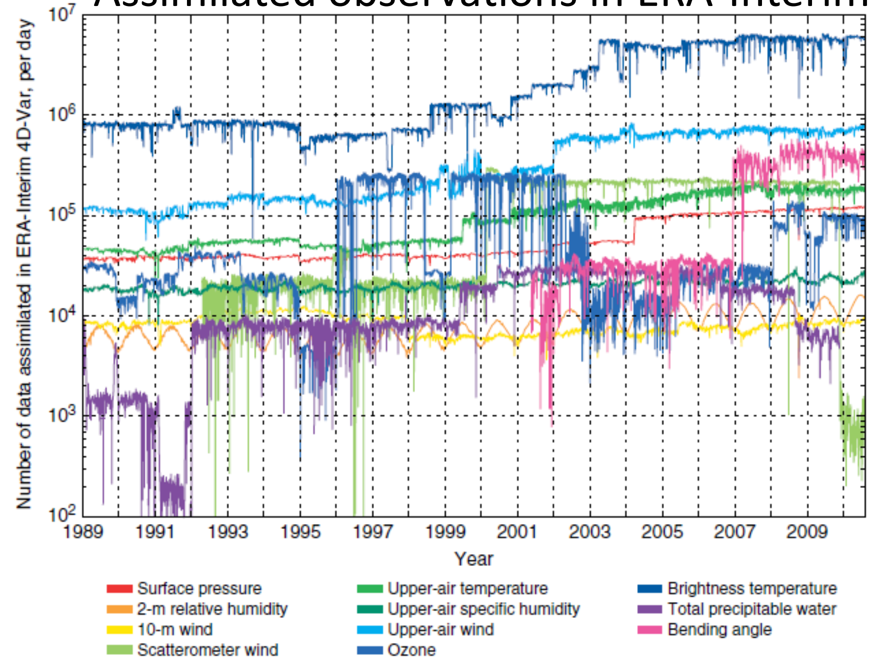
900hPa zonal mean zonal wind

DJF seasonal average, Analysis - Forecast



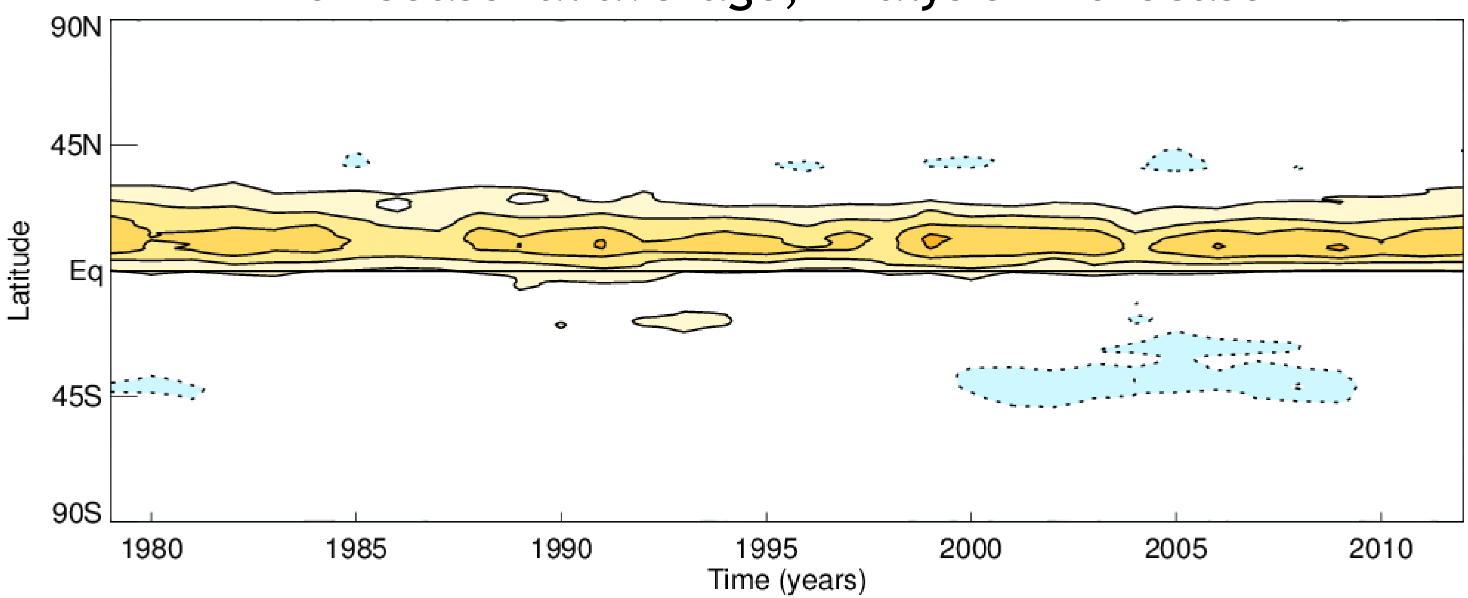


Assimilated observations in ERA-Interim

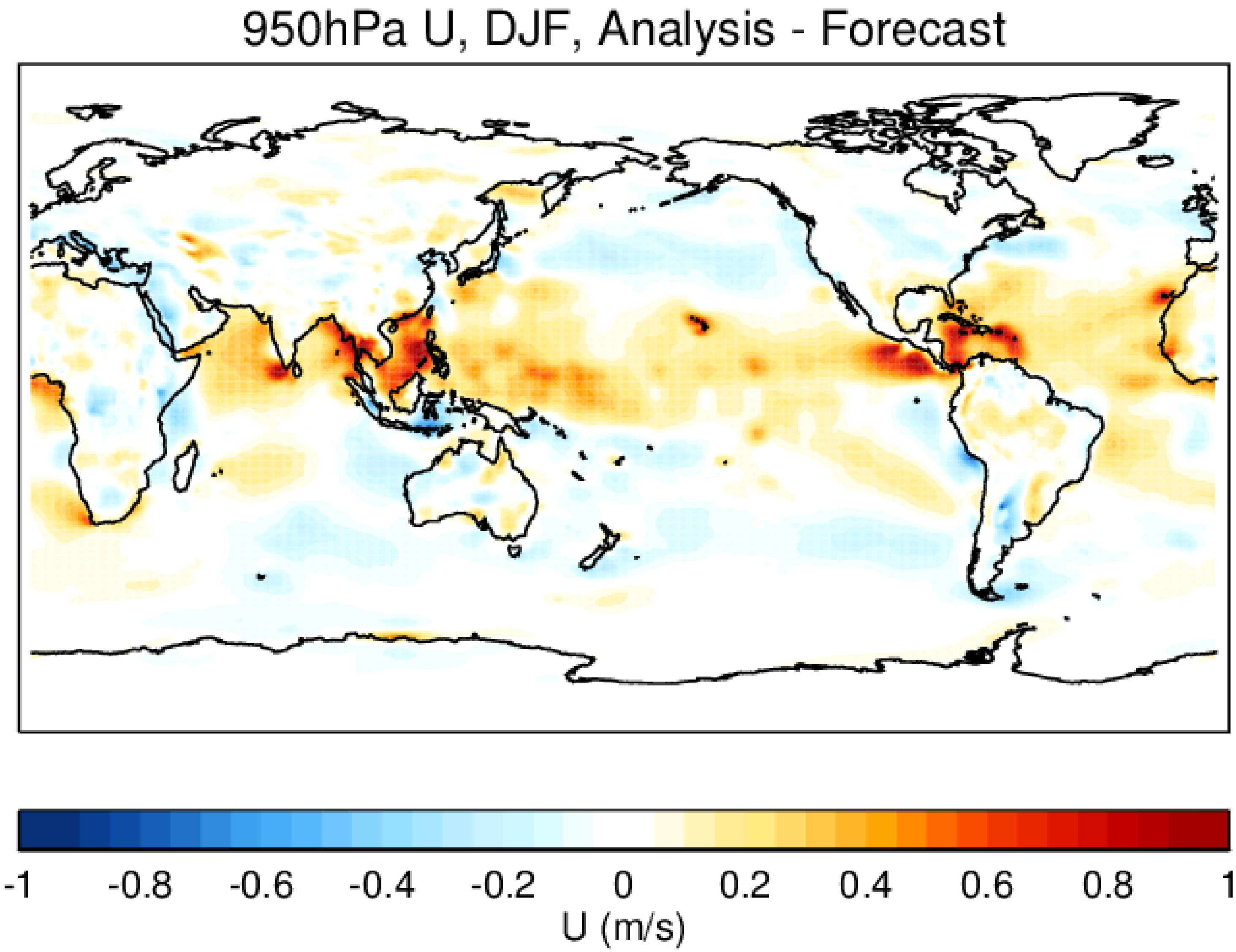


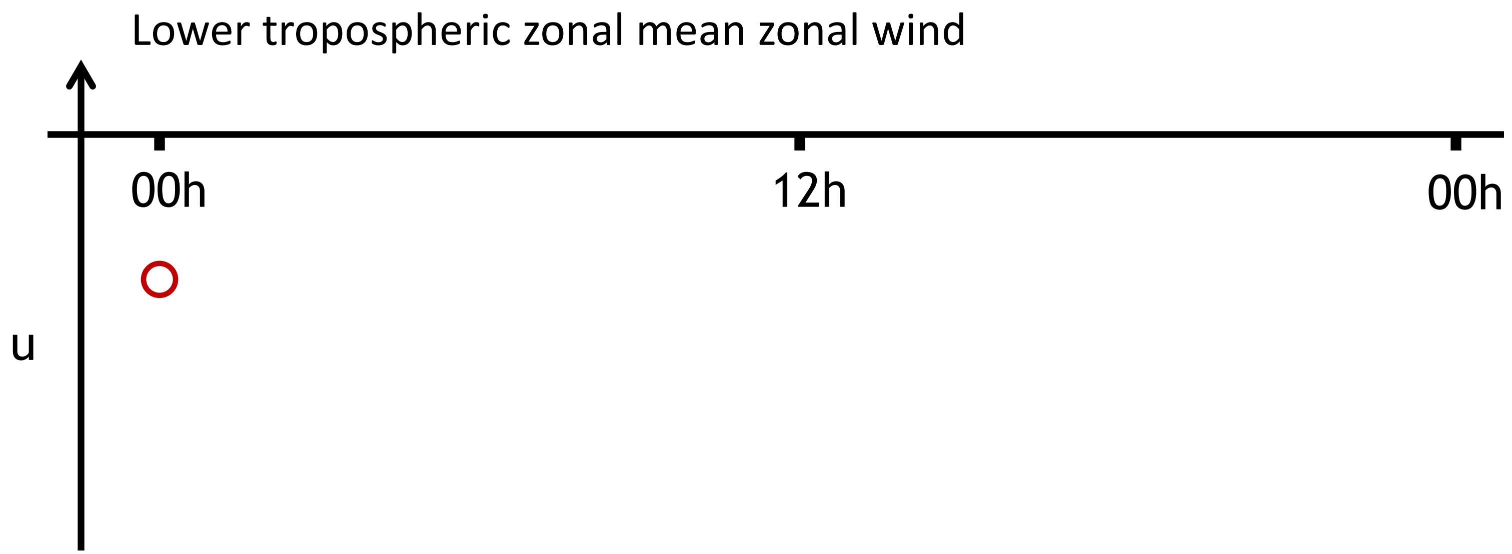
Dee et al 2011

DJF seasonal average, Analysis - Forecast

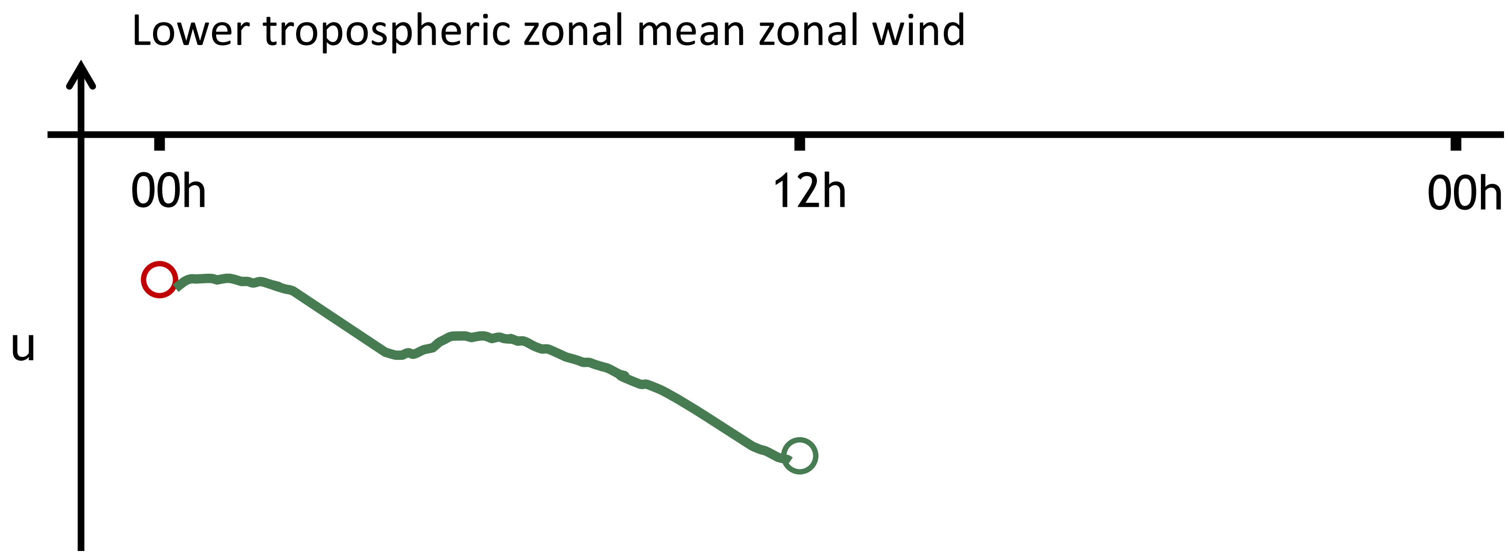


Lat-lon structure of analysis increments in DJF





Could this increment explain our budget residual?



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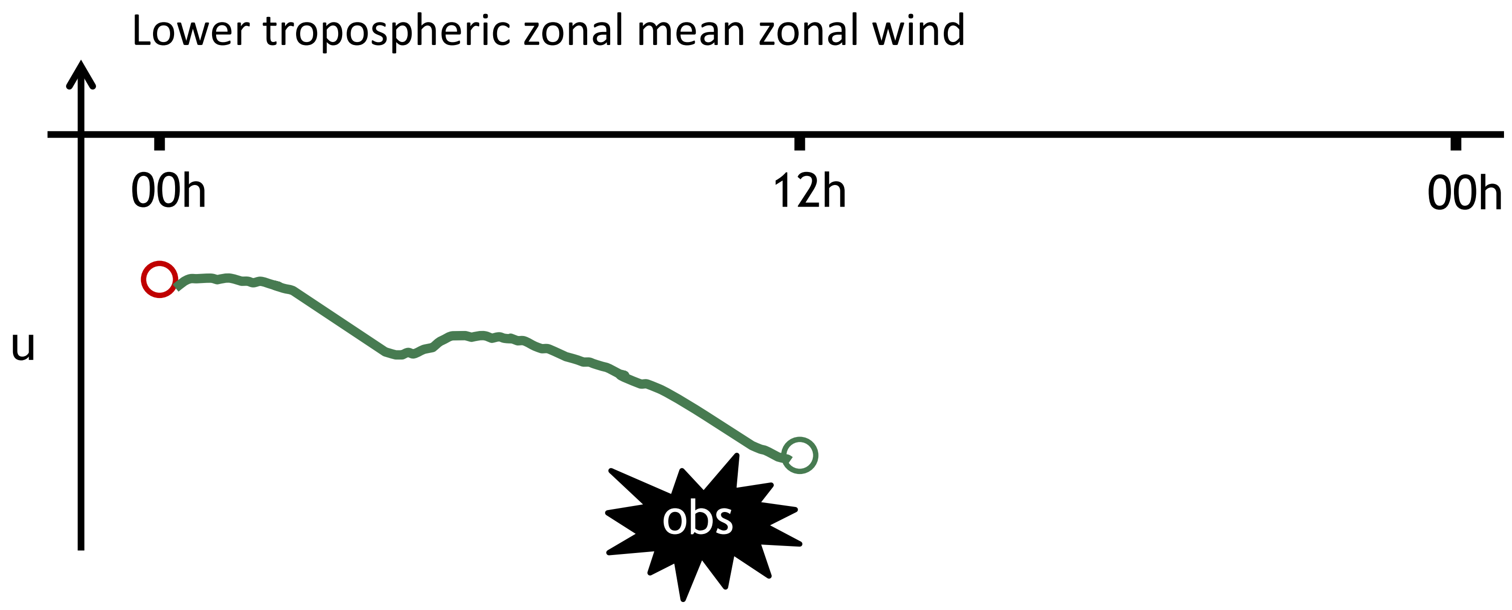

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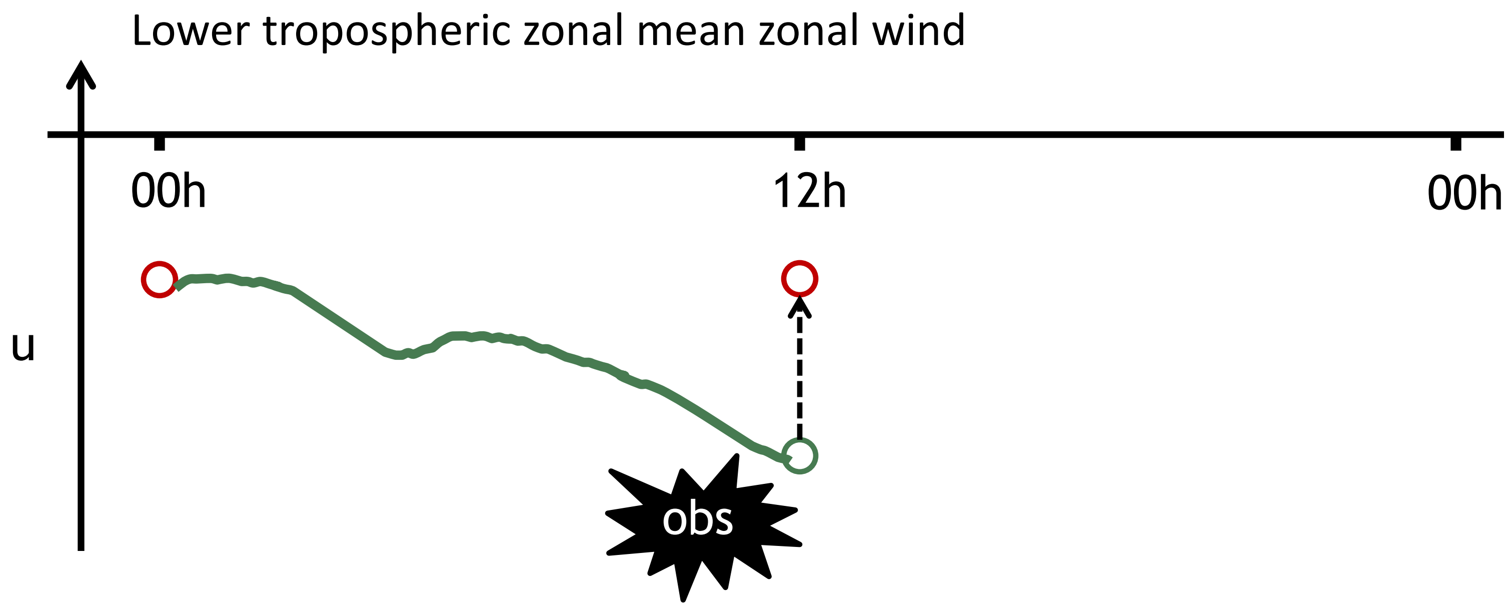

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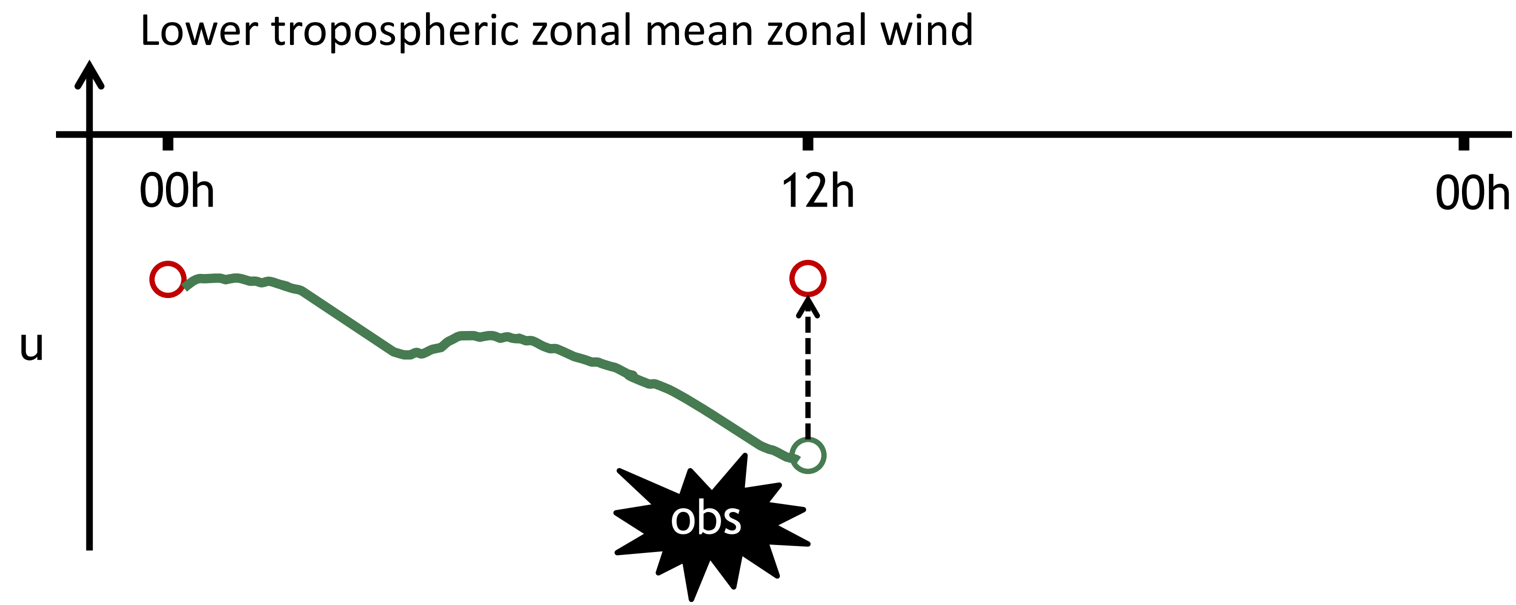
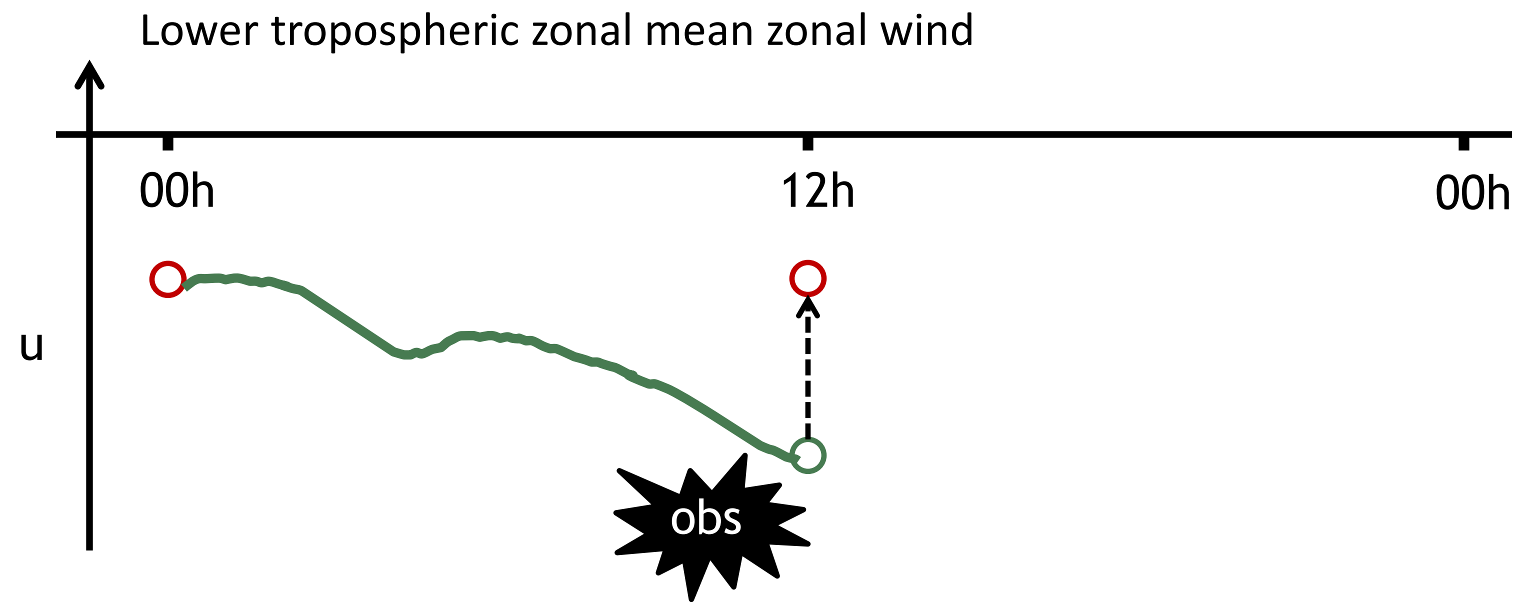


Could this increment explain our budget residual?

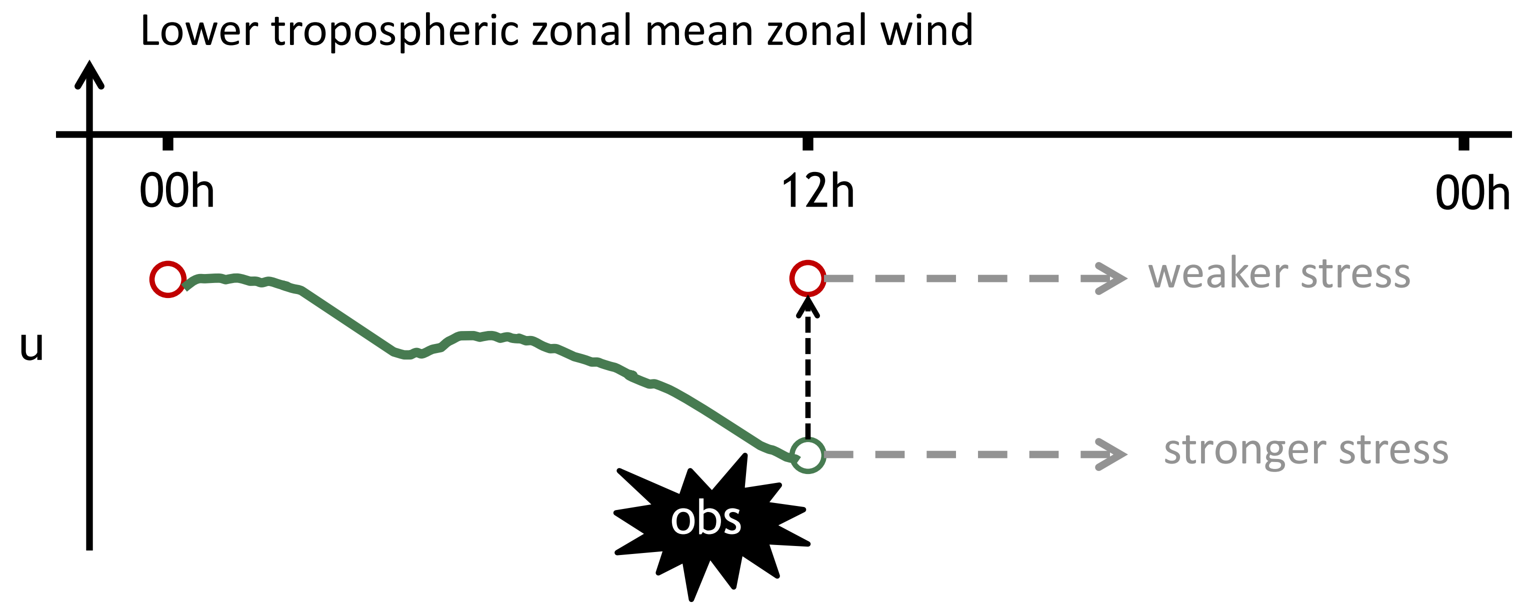
Surface Wind Stress ~ Lowest model level zonal wind



Could this increment explain our budget residual?

The surface stress field is accumulated over the 12h hour forecast

Surface Wind Stress ~ Lowest model level zonal wind



Could this increment explain our budget residual?

The surface stress field is accumulated over the 12h hour forecast

Surface Wind Stress	~	Lowest model level zonal wind

Assimilation of observations is providing a clear tendency to reduce the low level zonal mean easterly flow creating an imbalance in the vertically integrated momentum budget.

Assimilation of observations is providing a clear tendency to reduce the low level zonal mean easterly flow creating an imbalance in the vertically integrated momentum budget.

Possibilities

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Possibilities

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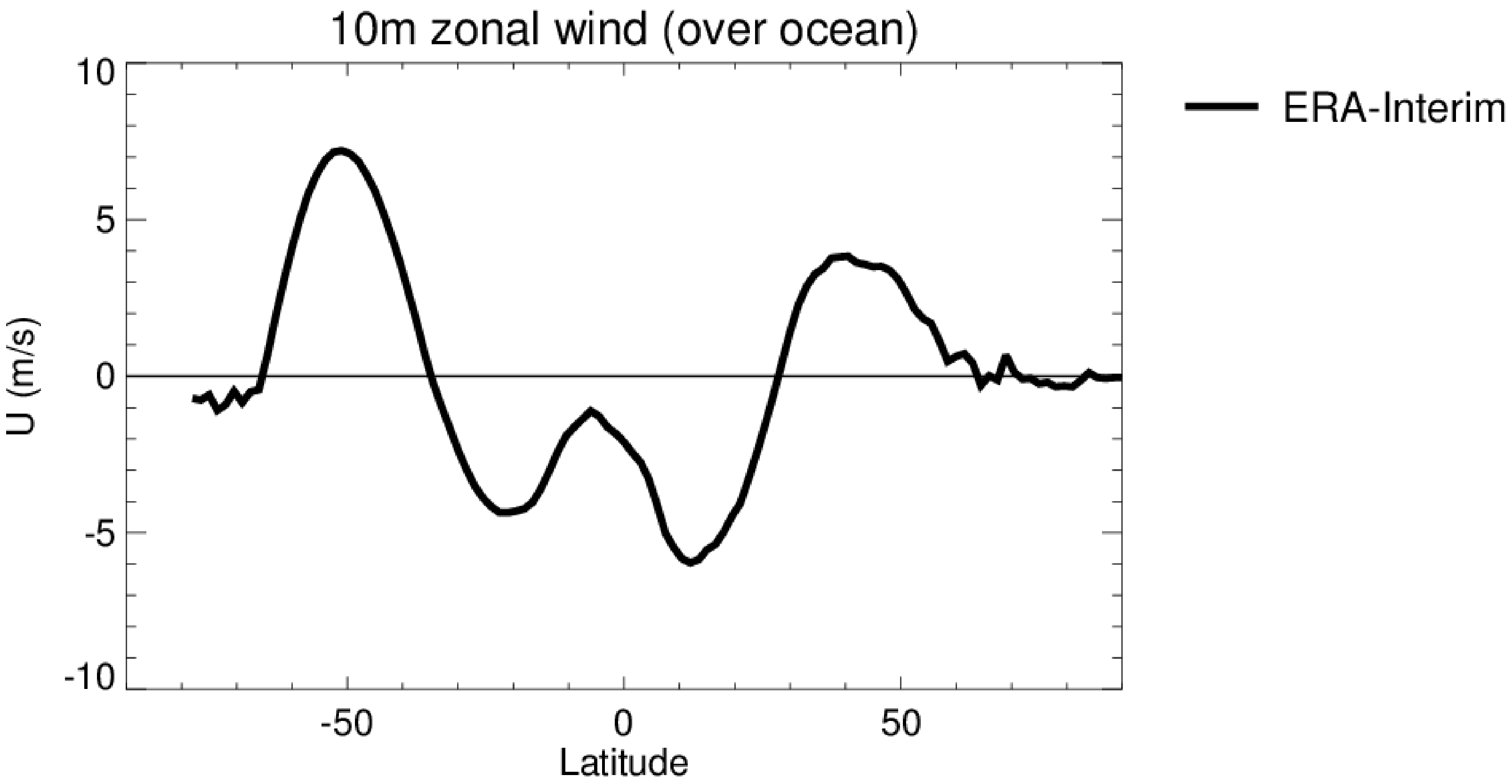
- The assimilation is incorrectly constraining the low level zonal mean flow.

- The assimilation is correctly constraining the flow at low levels and is accounting for something going wrong in the forecast model.

Is the low level flow in ERA-Interim correct?

- A comparison of 10m wind products over the ocean



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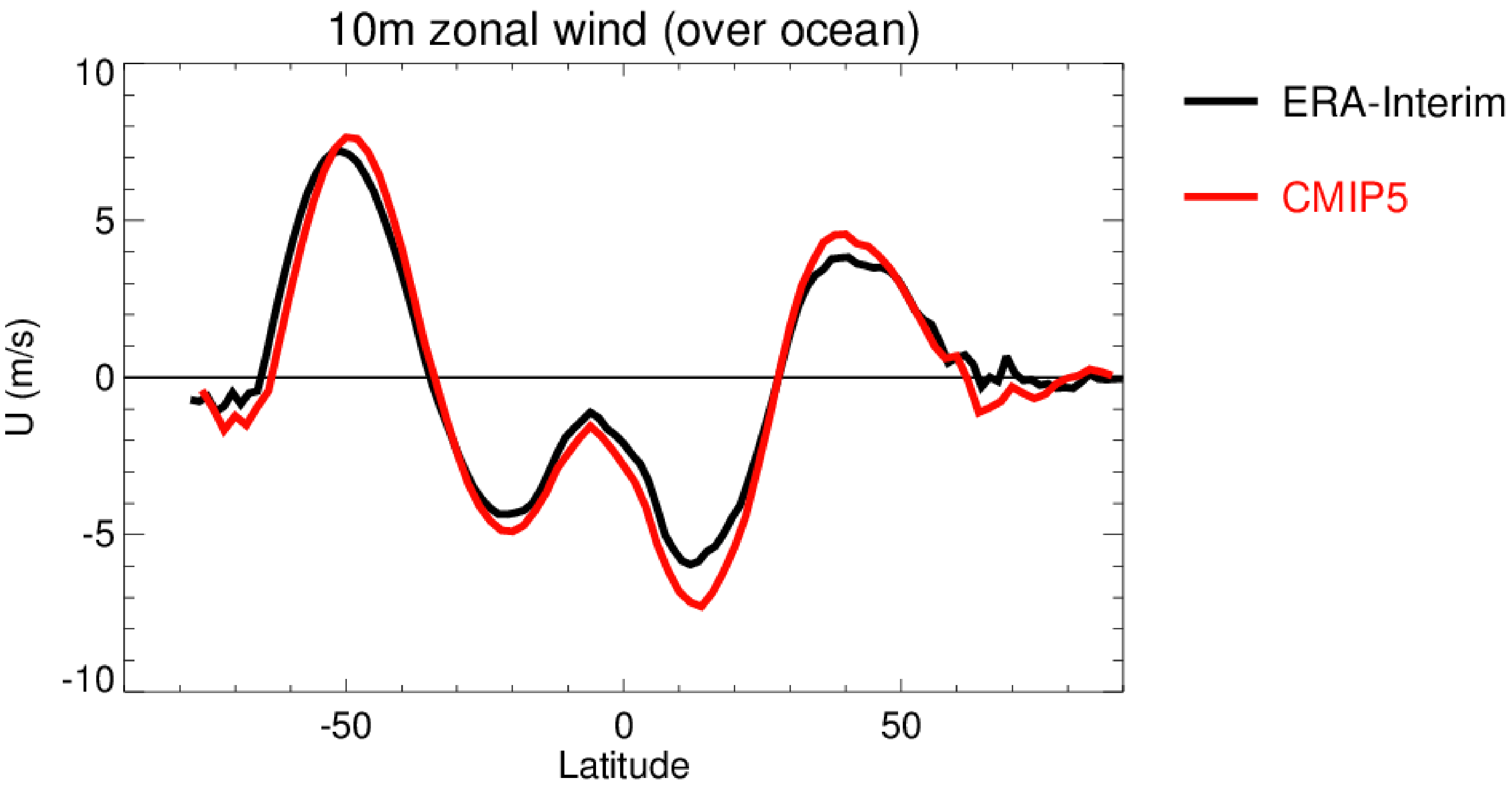

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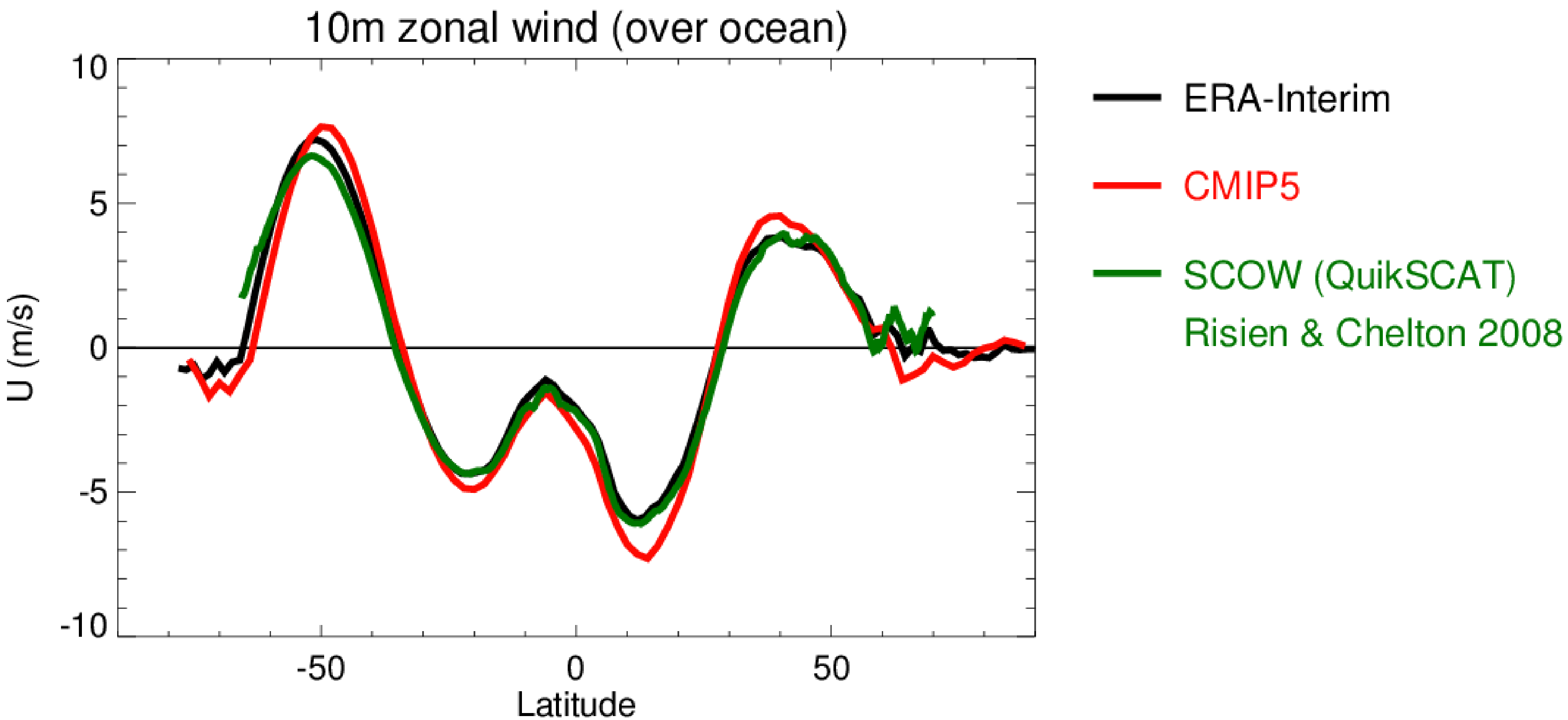

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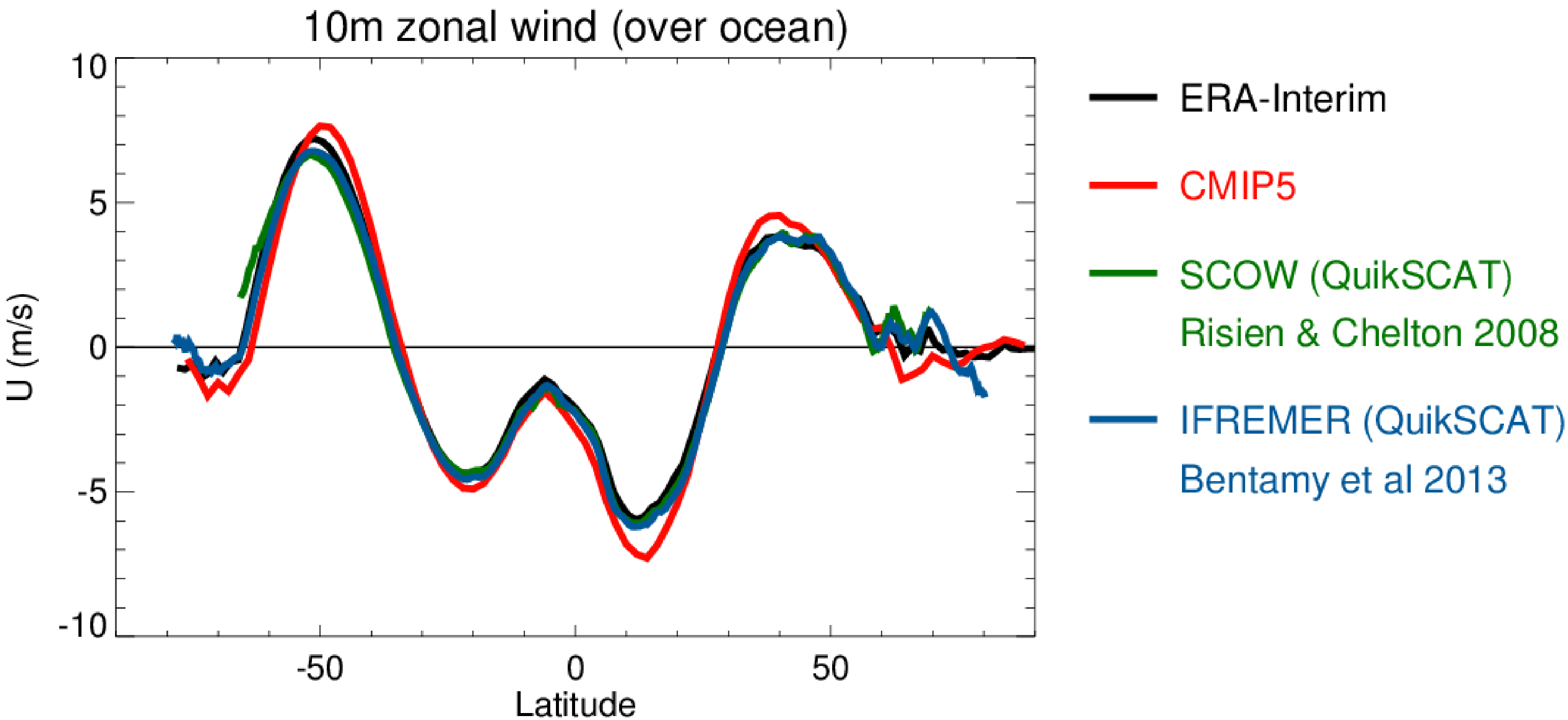

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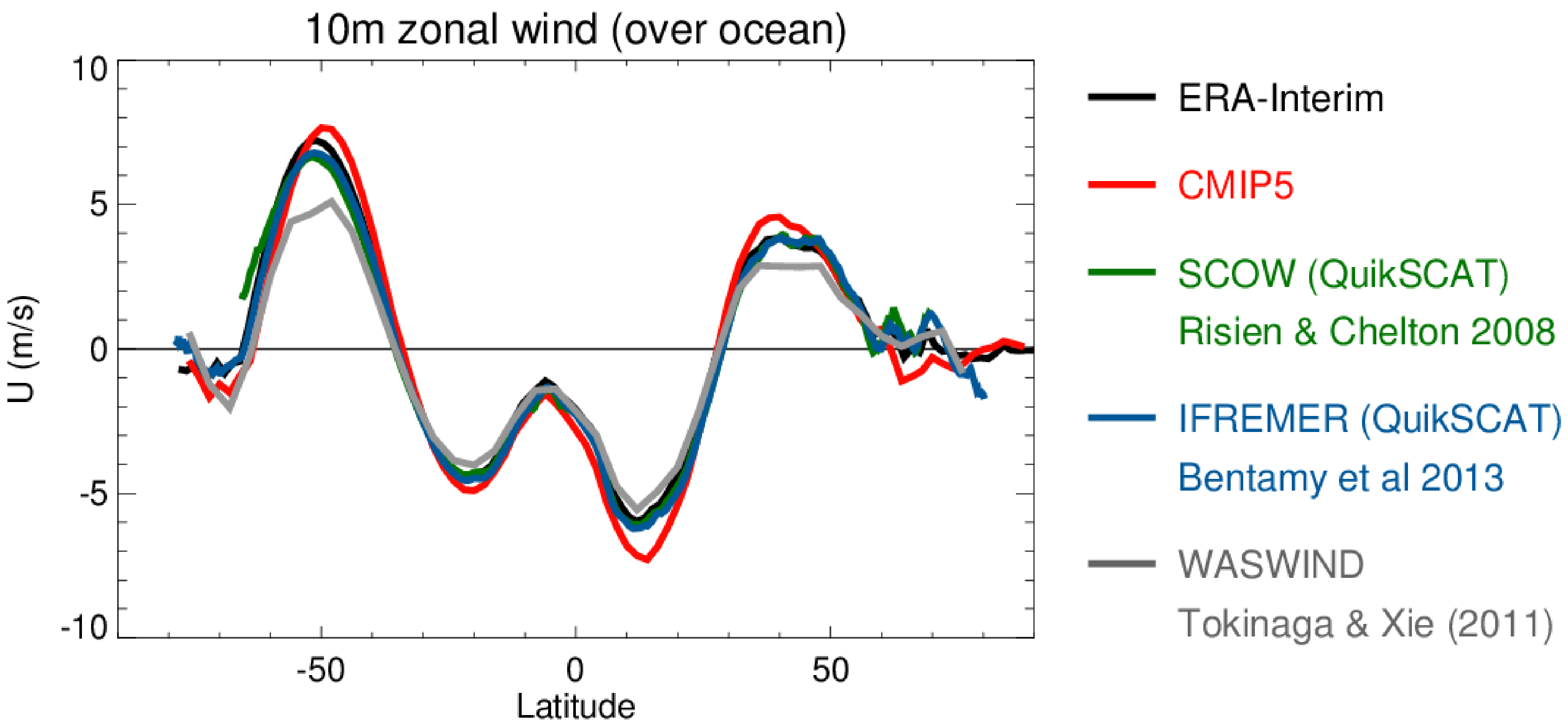

Assimilation of observations is providing a clear tendency to reduce the low level zonal mean easterly flow creating an imbalance in the vertically integrated momentum budget.

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- The assimilation is correctly constraining the flow at low levels. The increments are, therefore, accounting for something going wrong in the forecast model. 

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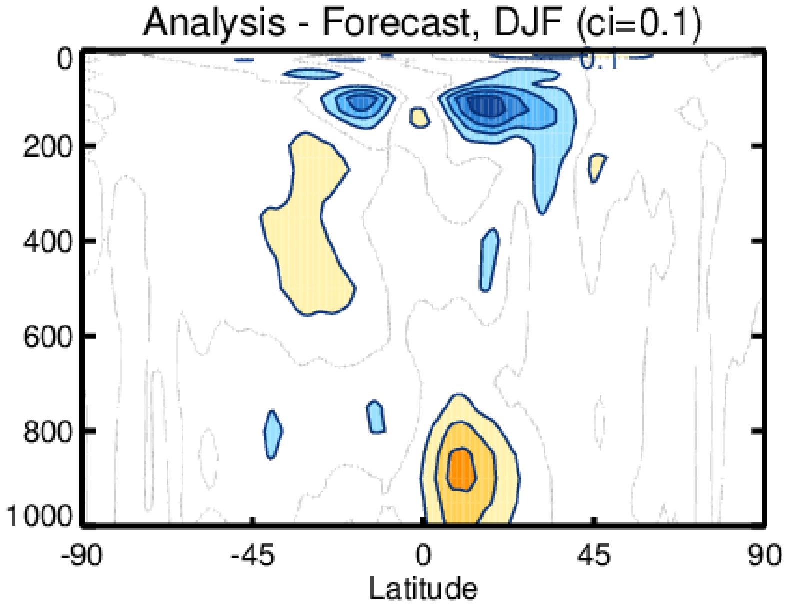
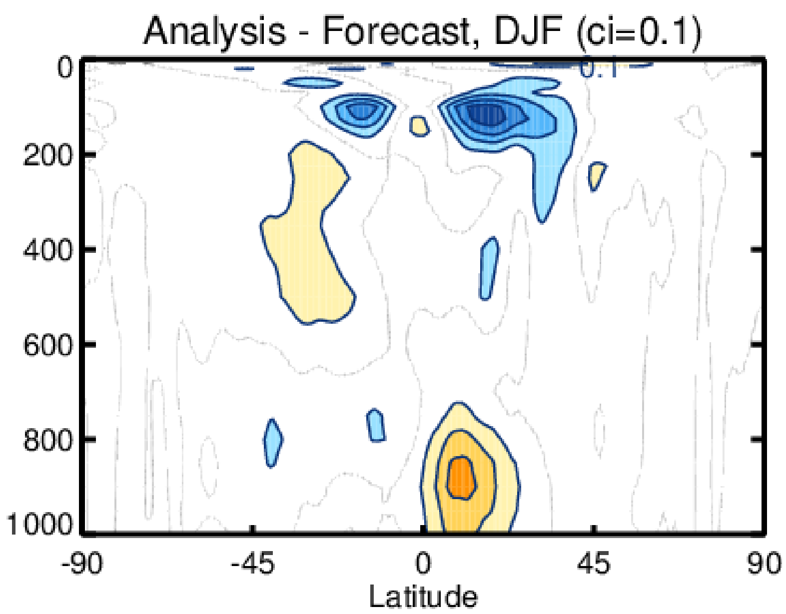
An understanding of this may help to understand issues in the CMIP models as well.

Zonal mean U

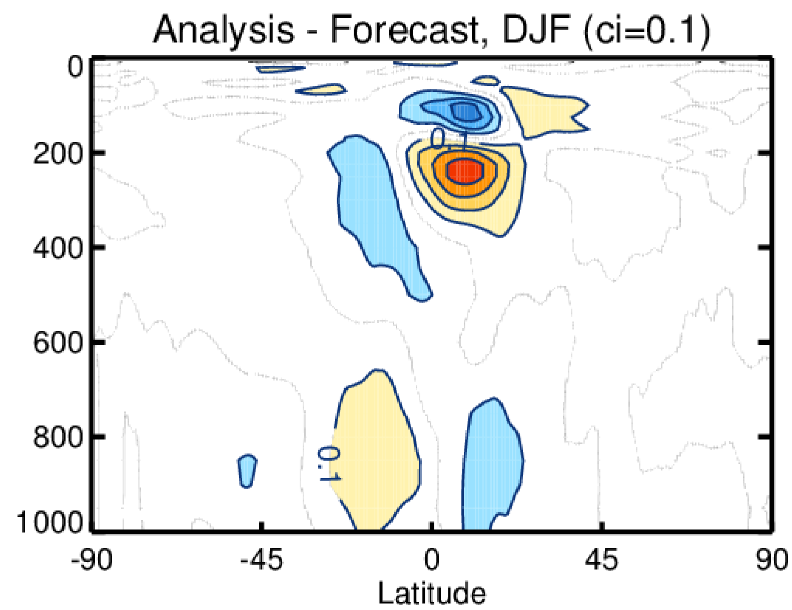
(Analysis – Forecast)



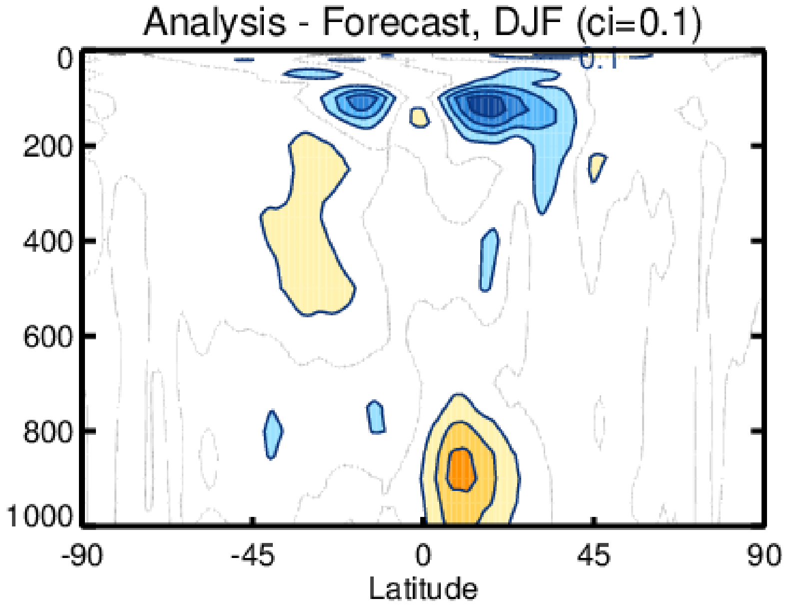
Zonal mean U
(Analysis – Forecast)



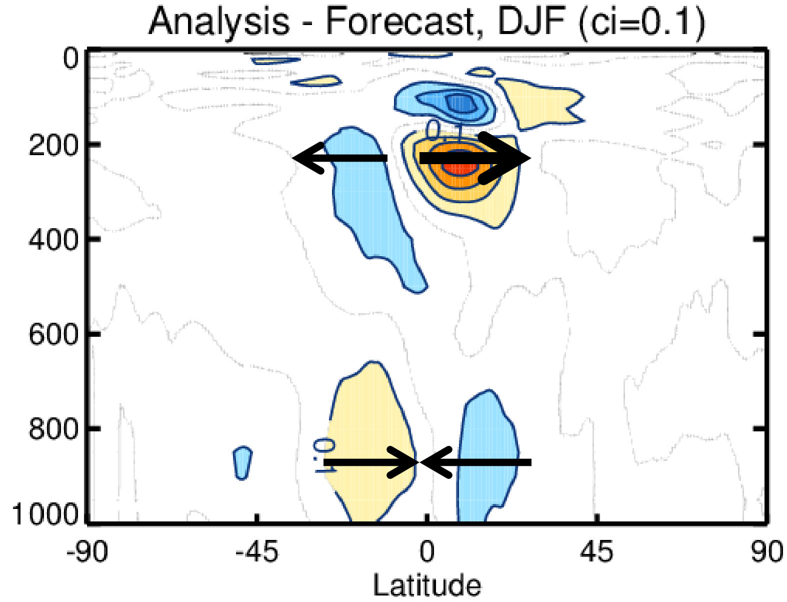
Zonal mean V
(Analysis – Forecast)



Zonal mean U
(Analysis – Forecast)



Zonal mean V
(Analysis – Forecast)



Zonal mean U
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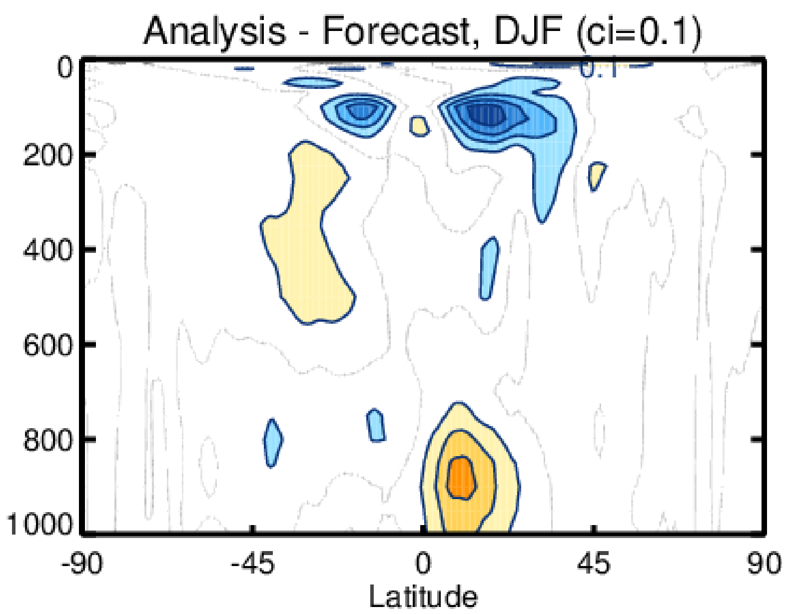
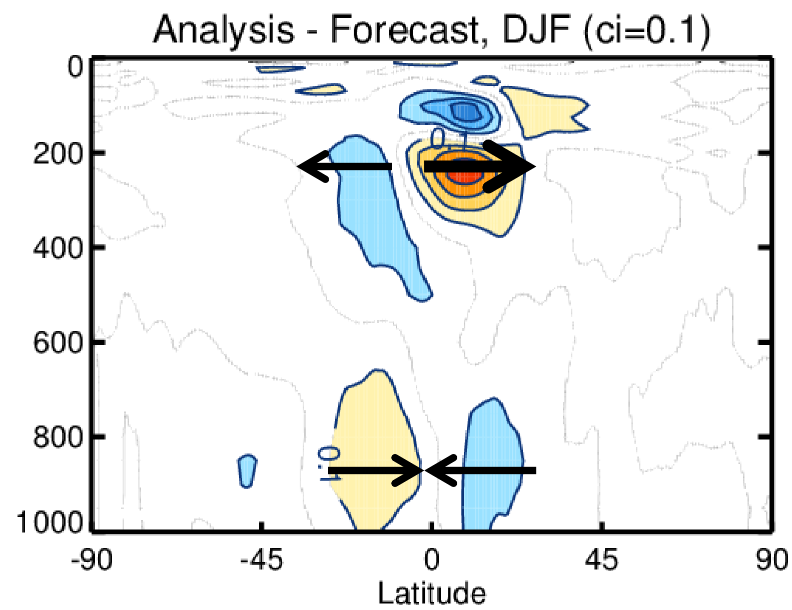
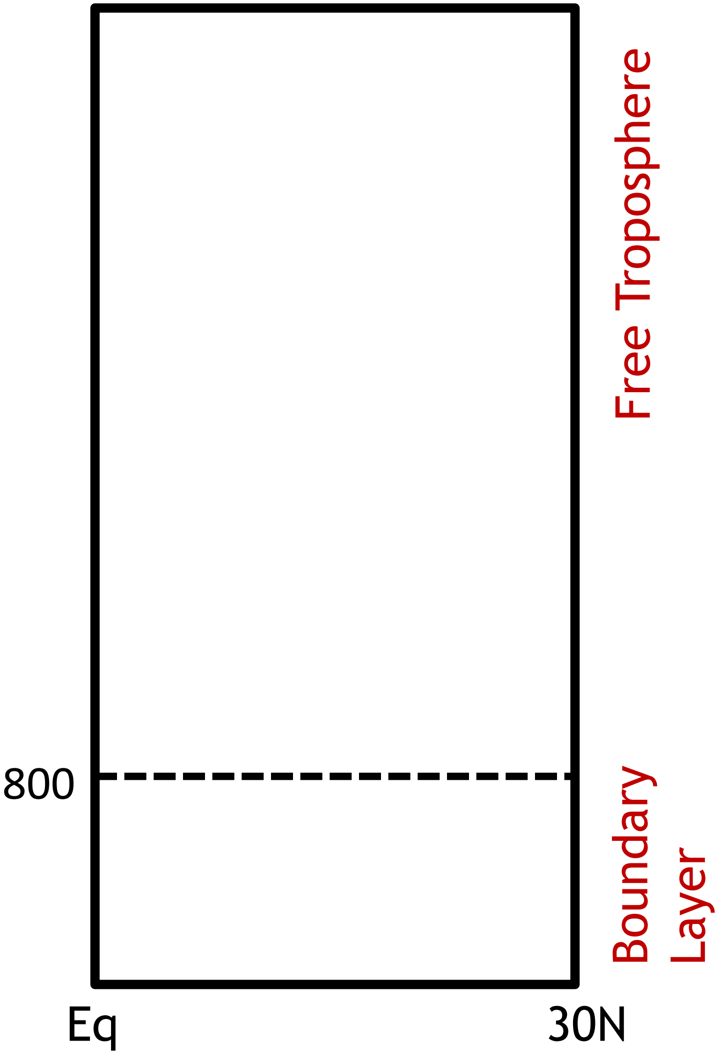


Zonal mean V
(Analysis – Forecast)

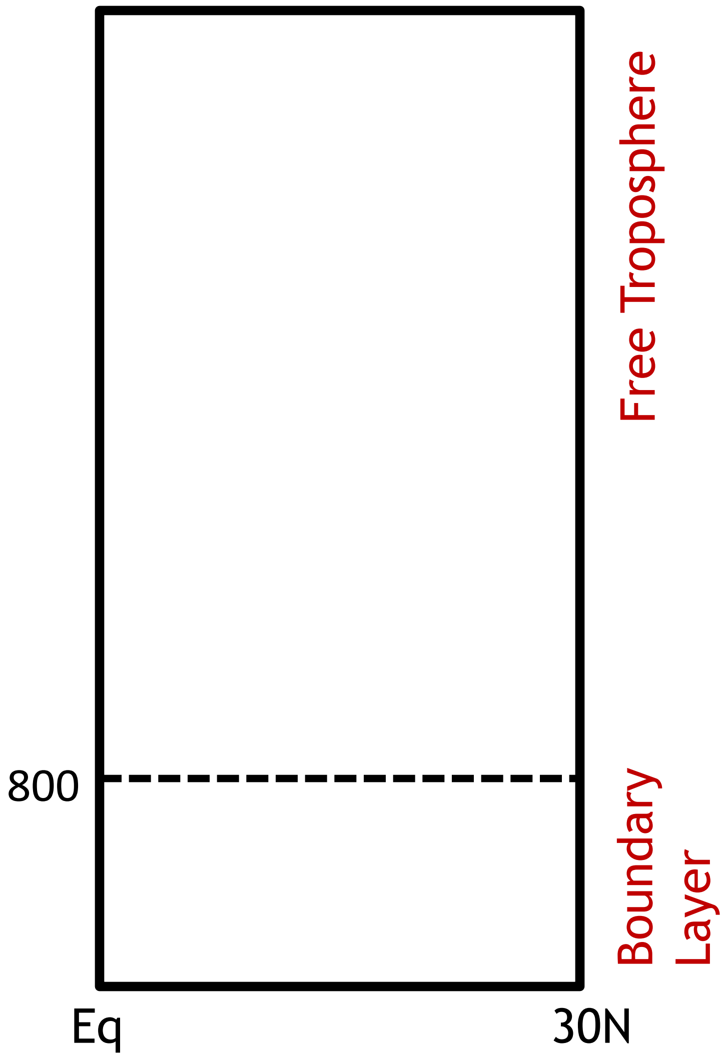


Assimilation weakens the low level easterlies, but strengthens the Hadley circulation

Local Zonal Momentum Balances



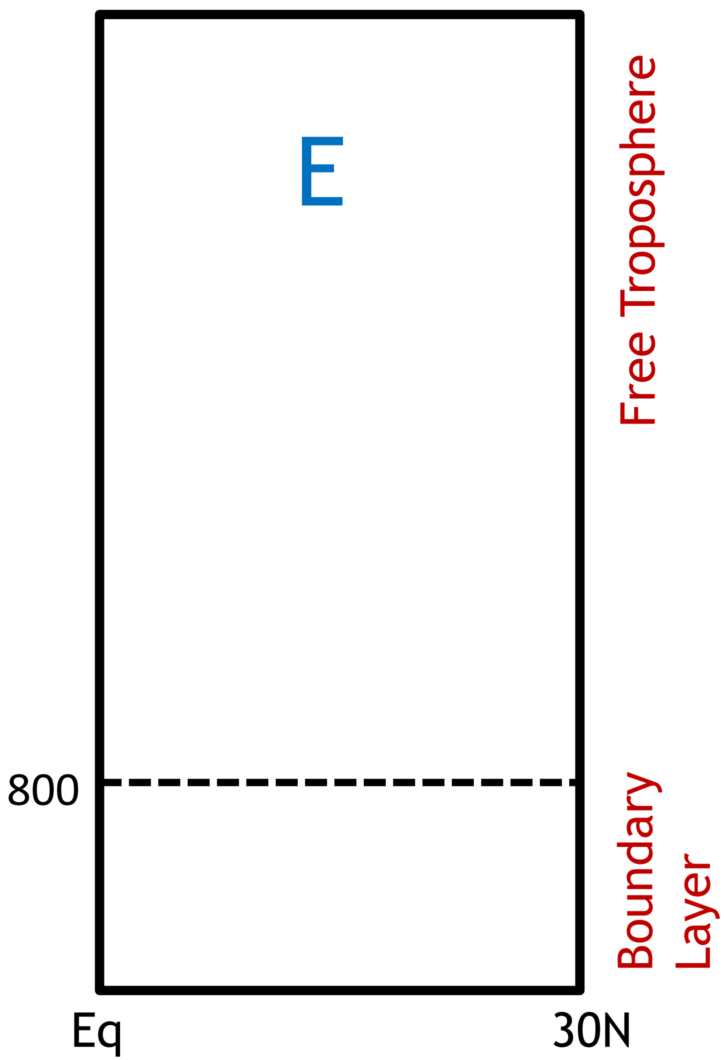
Local Zonal Momentum Balances



Dominant Balance in the Free troposphere:

$$\frac{\partial u}{\partial t} = fv + UV_{conv}$$

Local Zonal Momentum Balances



Dominant Balance in the Free troposphere:

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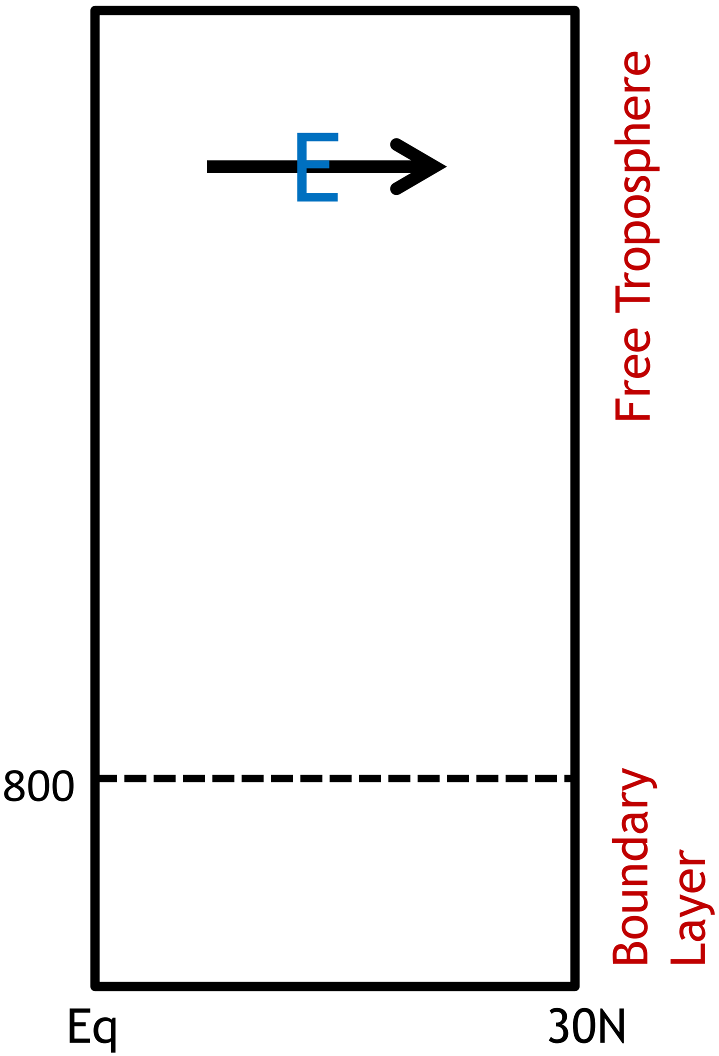
E

Local Zonal Momentum Balances



Dominant Balance in the Free troposphere:

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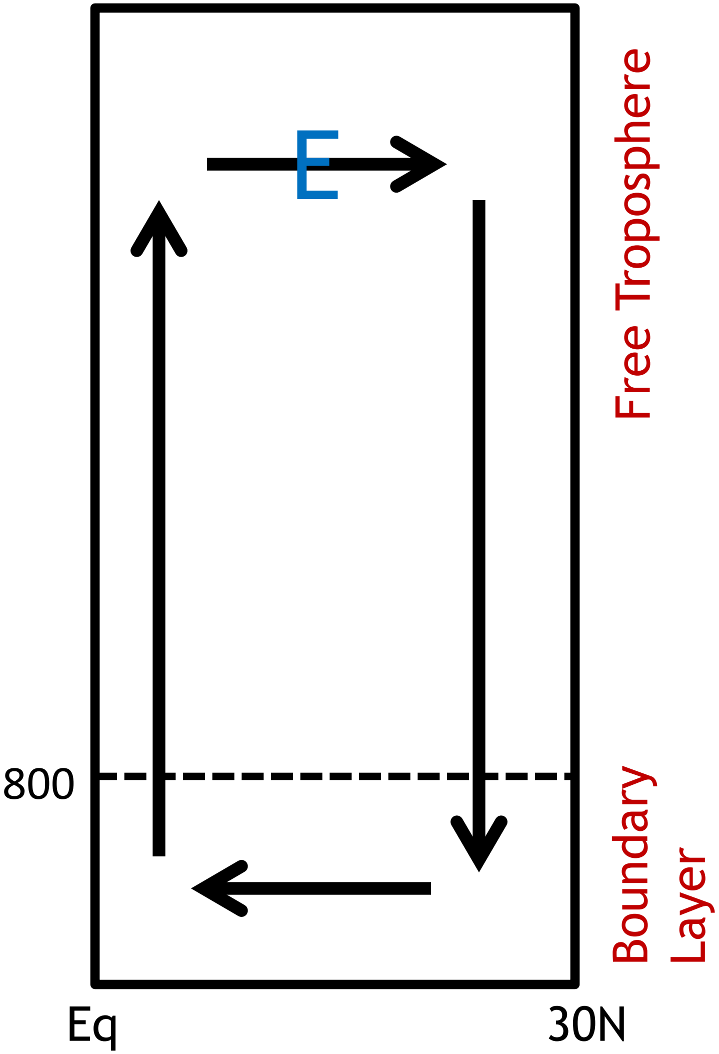
Local Zonal Momentum Balances



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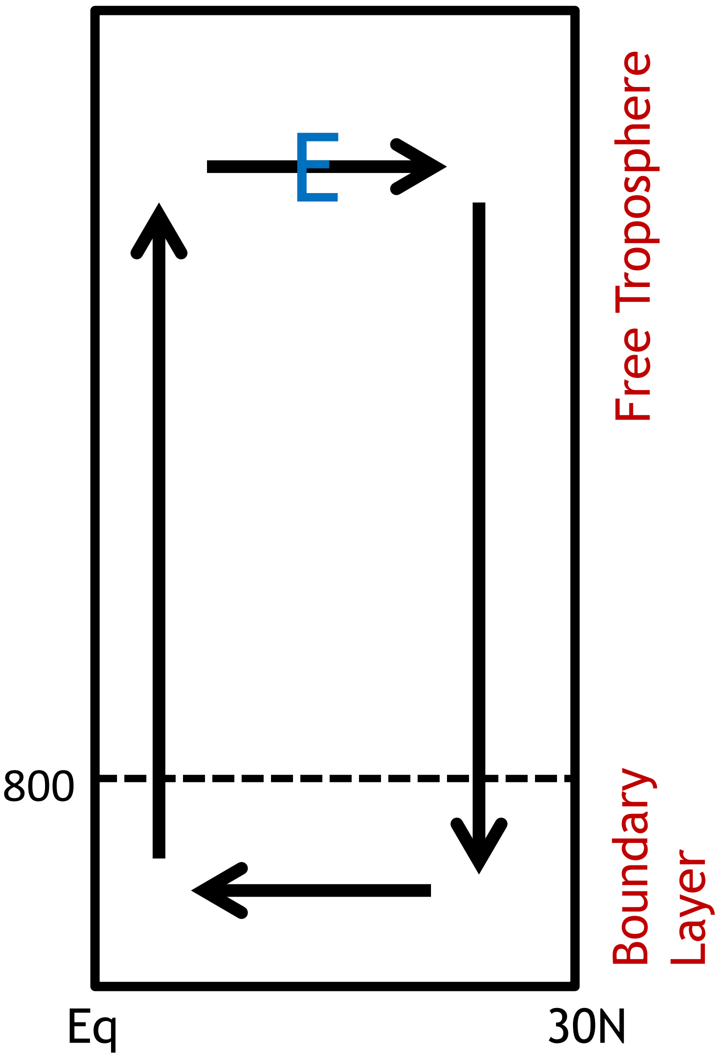
Local Zonal Momentum Balances



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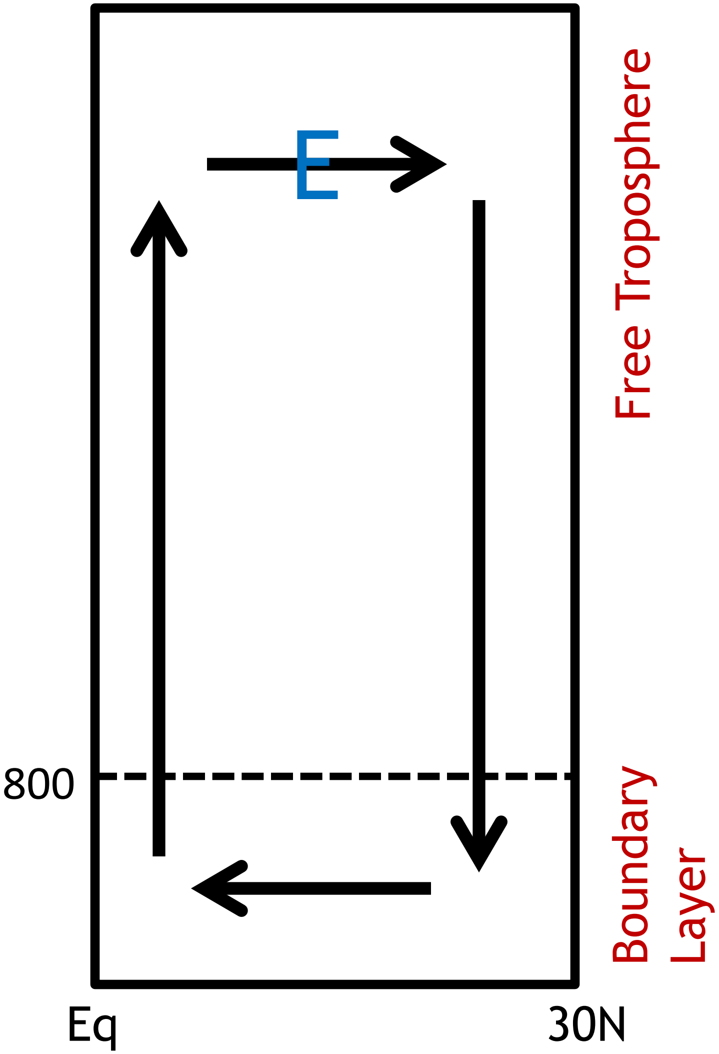
Local Zonal Momentum Balances



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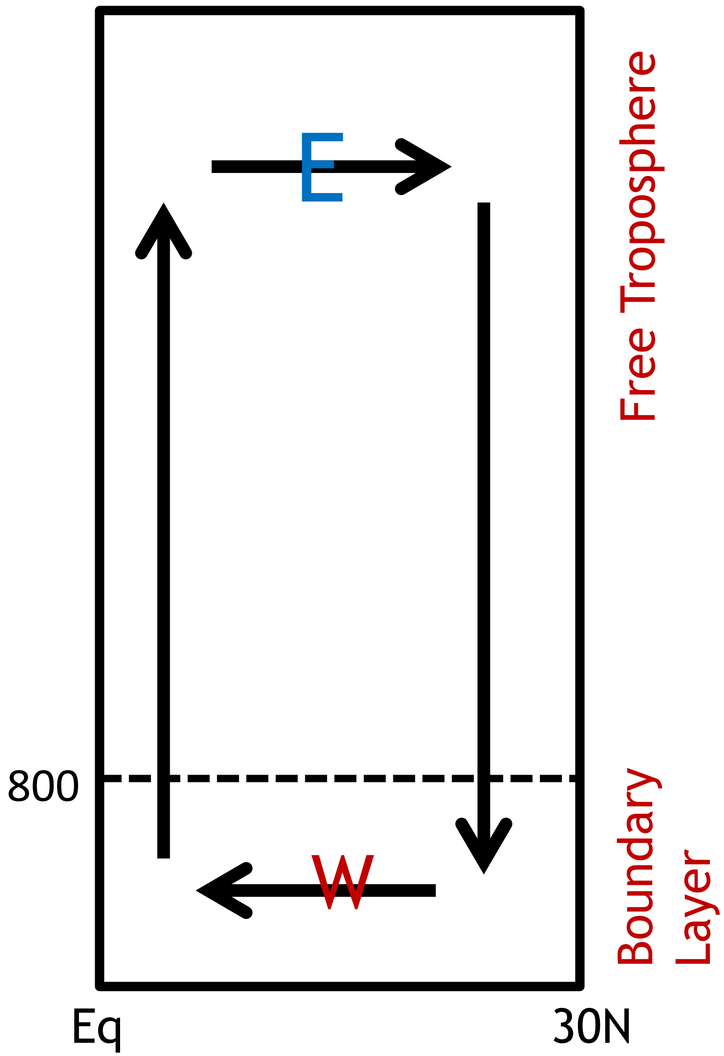
Local Zonal Momentum Balances



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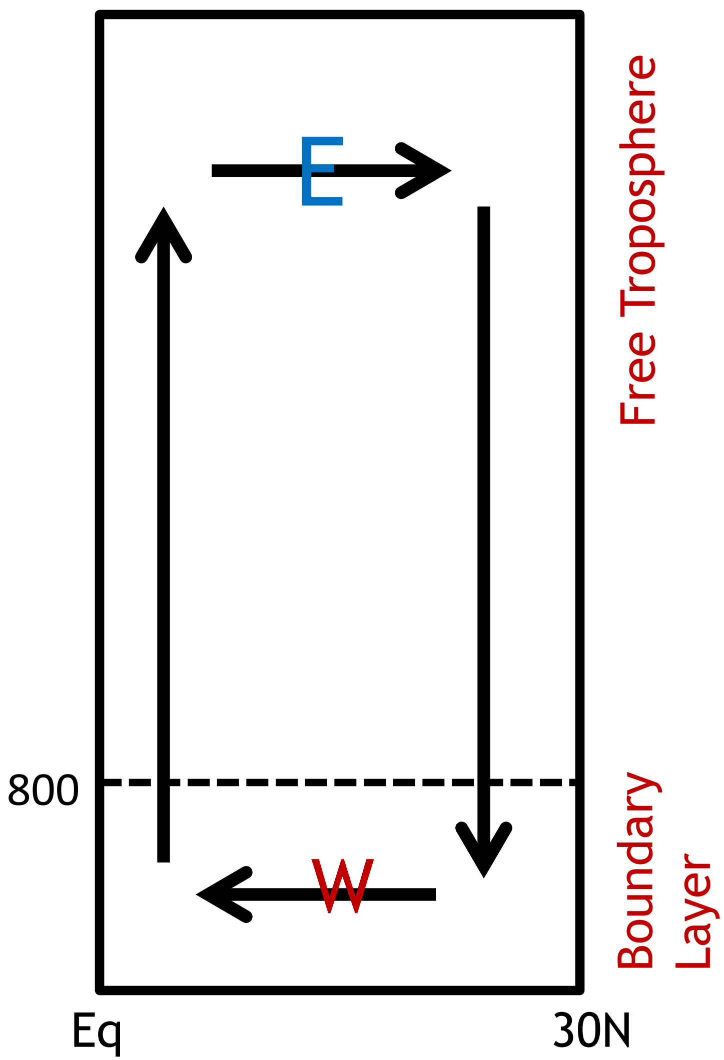
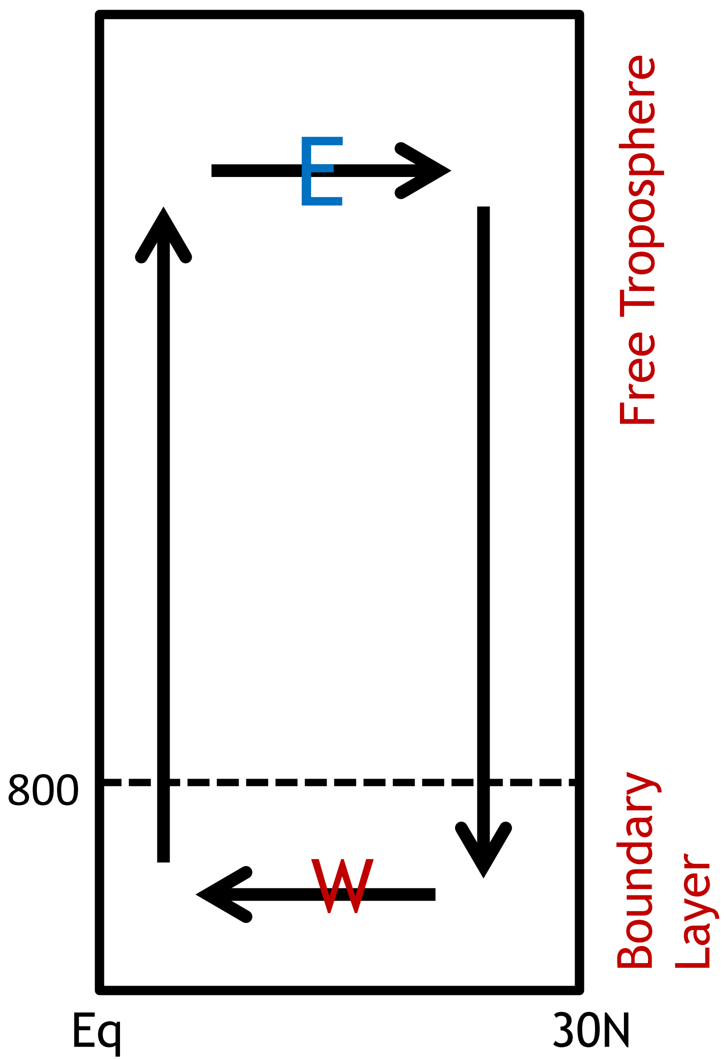
Local Zonal Momentum Balances



Where might things be going wrong?

Free troposphere or Boundary Layer?

Local Zonal Momentum Balances

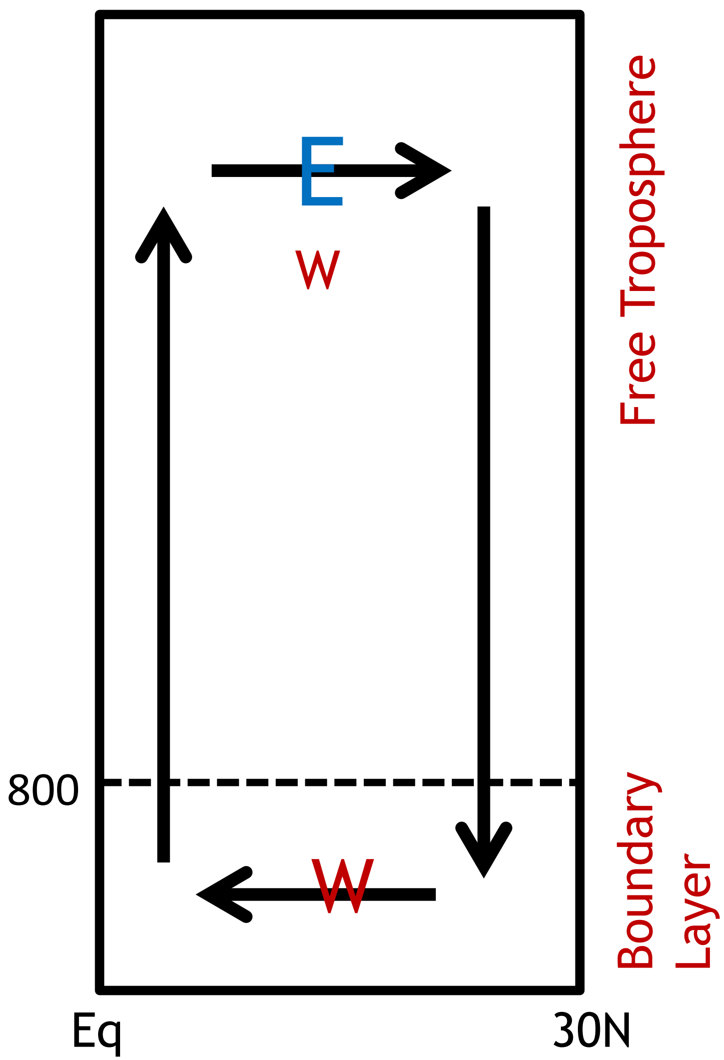


Where might things be going wrong?

Free troposphere or Boundary Layer?

Could be missing a westerly forcing in the free troposphere e.g., missing physics, incorrect resolved dynamics.

Local Zonal Momentum Balances



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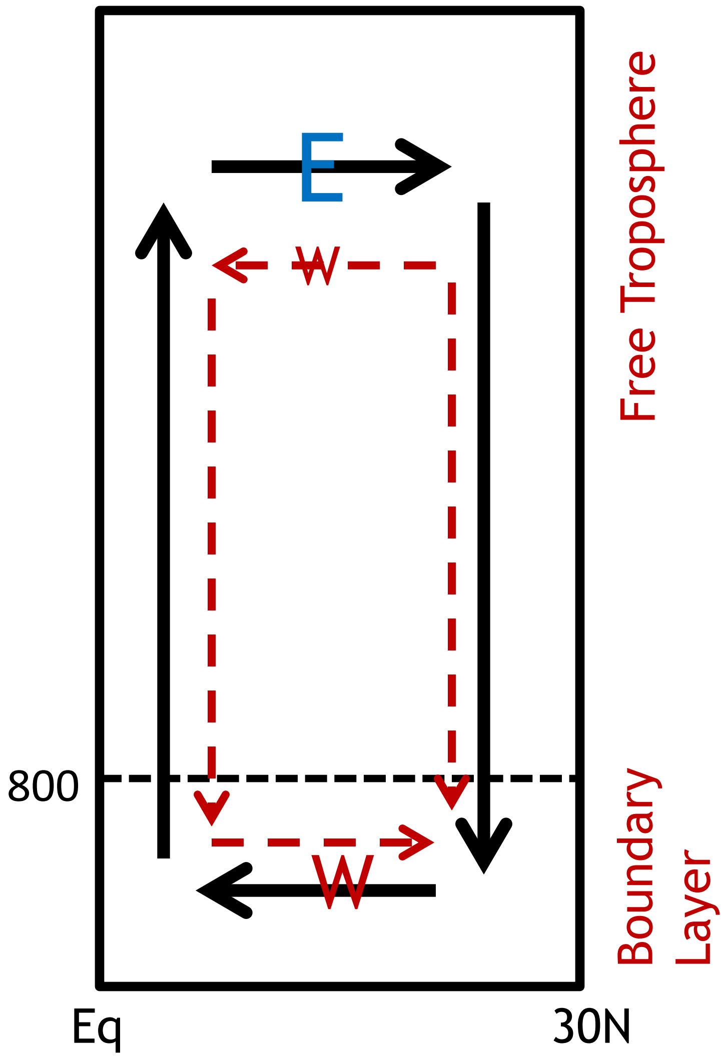

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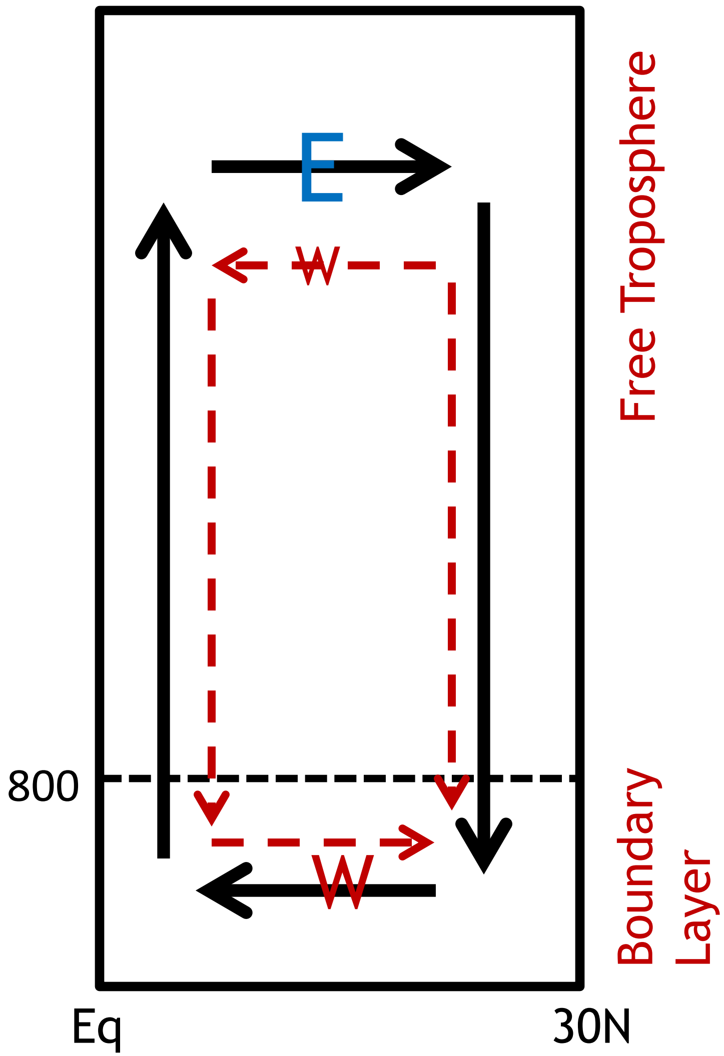
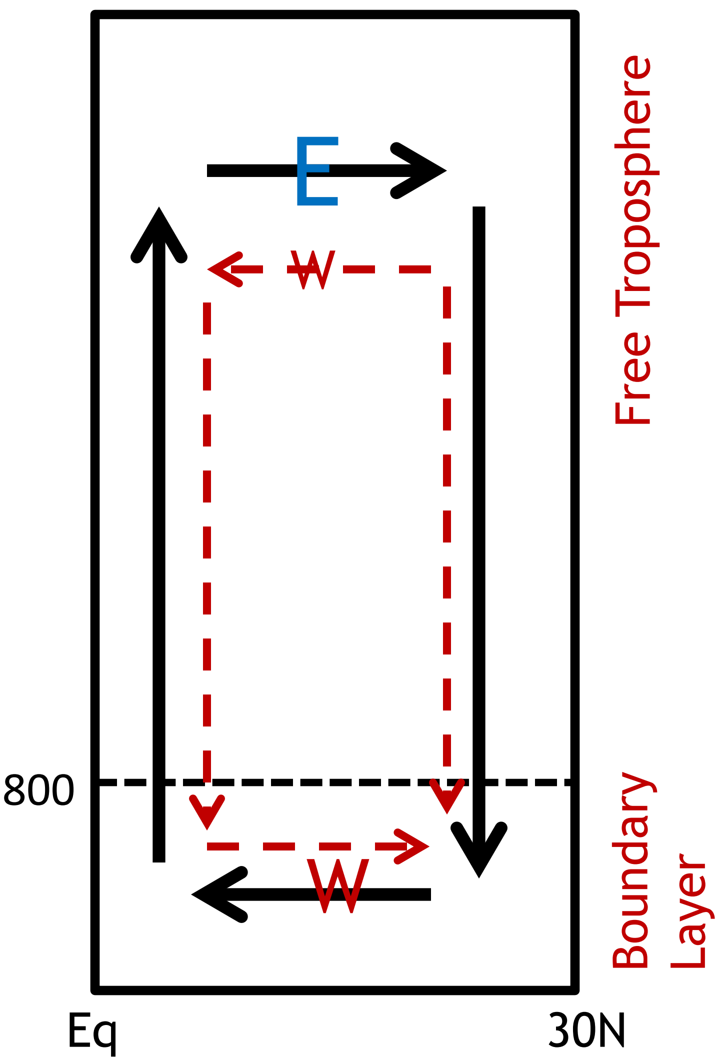


If we are missing a westerly forcing in the upper troposphere…

Local Zonal Momentum Balances



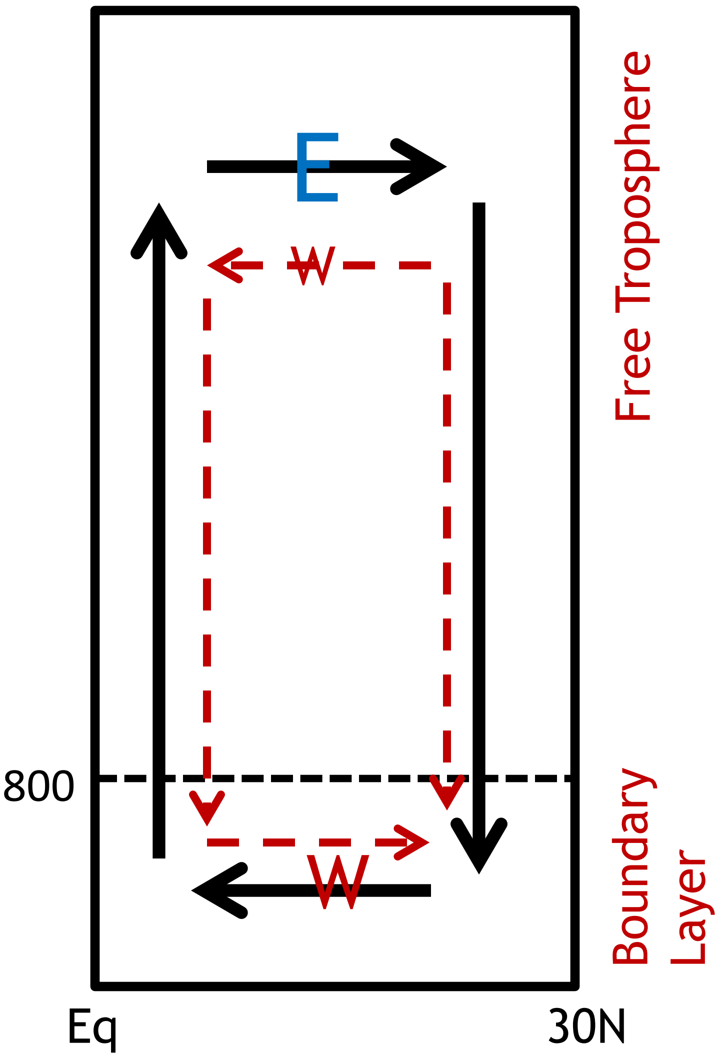
If we are missing a westerly forcing in the upper troposphere…

How would we expect things to evolve over the forecast?

$$\frac{\partial u}{\partial t} = fv + UV_{conv} + Z$$

0 W E W

Local Zonal Momentum Balances



If we are missing a westerly forcing in the upper troposphere…

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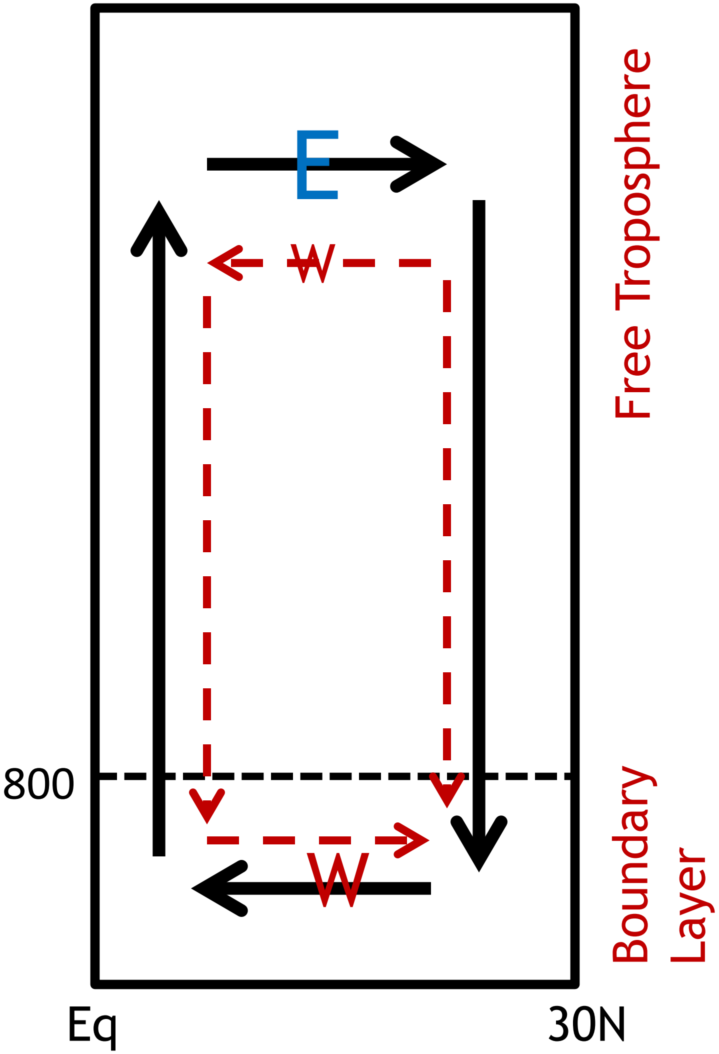
$$\frac{\partial u}{\partial t} = fv + UV_{conv} + Z$$

0 W E $\cancel{\text{W}}$

Local Zonal Momentum Balances



If we are missing a westerly forcing in the upper troposphere…

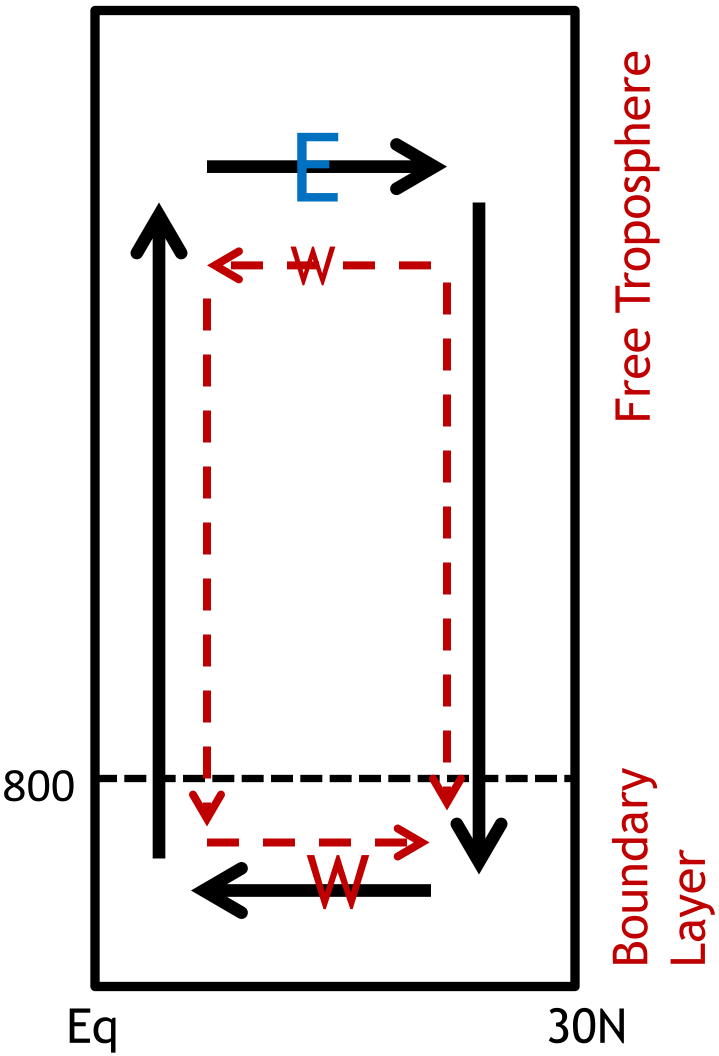
How would we expect things to evolve over the forecast?

$$\frac{\partial u}{\partial t} = fv + UV_{conv} + Z$$

0 W E $\cancel{\text{W}}$

Imbalance $\longrightarrow$ E ↑

Local Zonal Momentum Balances



If we are missing a westerly forcing in the upper troposphere…

How would we expect things to evolve over the forecast?

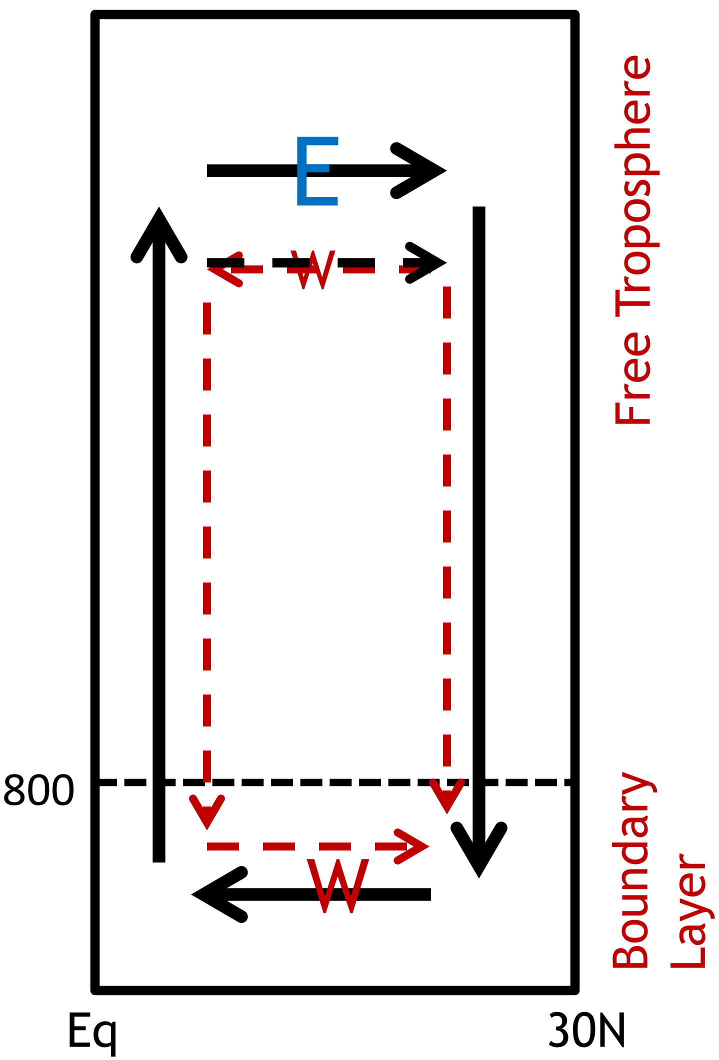
We'd expect…

An easterly acceleration in the upper troposphere

$$\frac{\partial u}{\partial t} = fv + UV_{conv} + Z$$

$\frac{\partial u}{\partial t}$	fv	UV_{conv}	Z
0	W	E	$\cancel{\text{W}}$
E ↑			E ↑

Local Zonal Momentum Balances



If we are missing a westerly forcing in the upper troposphere…

How would we expect things to evolve over the forecast?

We'd expect…

An easterly acceleration in the upper troposphere

and/or

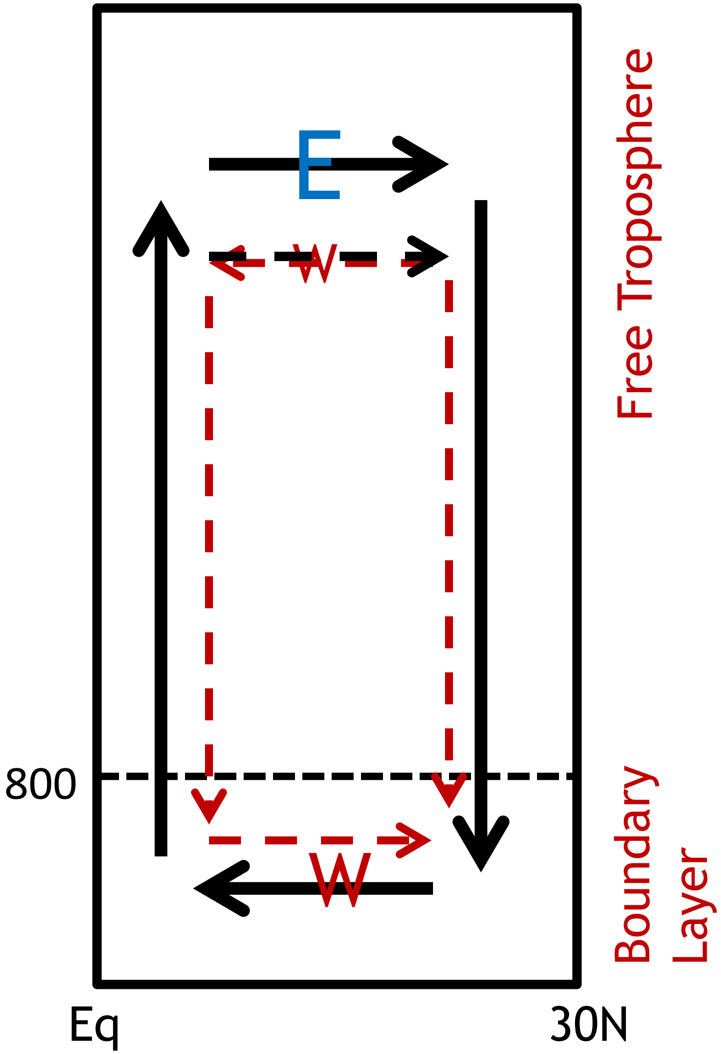
The upper level Southerlies to strengthen

$$\frac{\partial u}{\partial t} = fv + UV_{conv} + Z$$

0 W E ~~W~~

E W E

Local Zonal Momentum Balances



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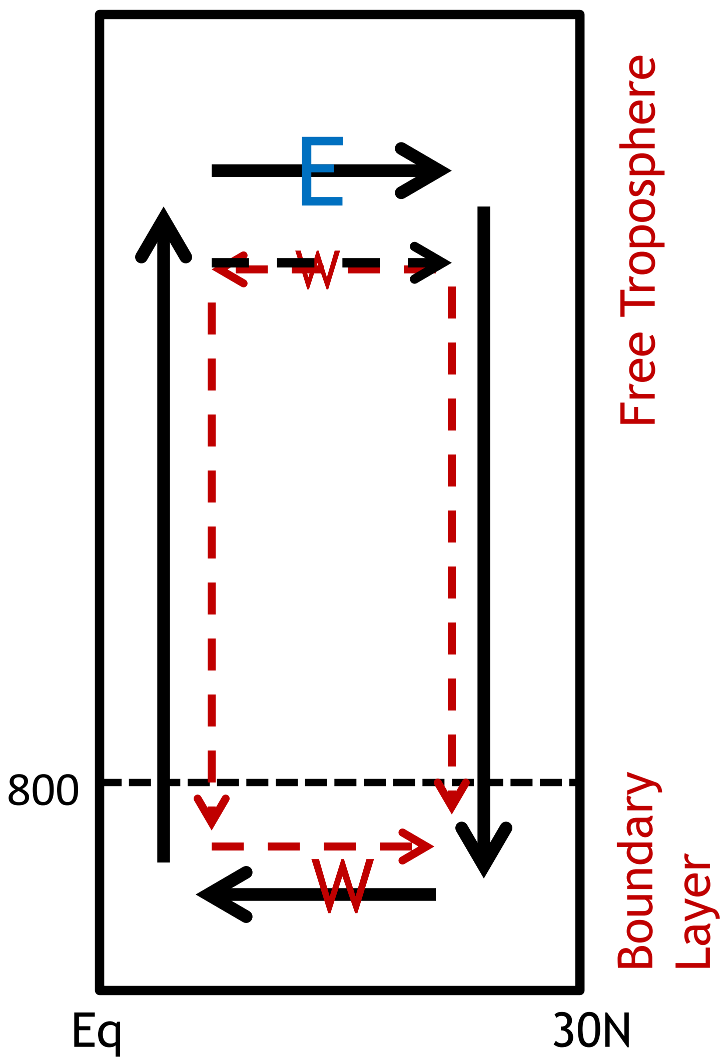

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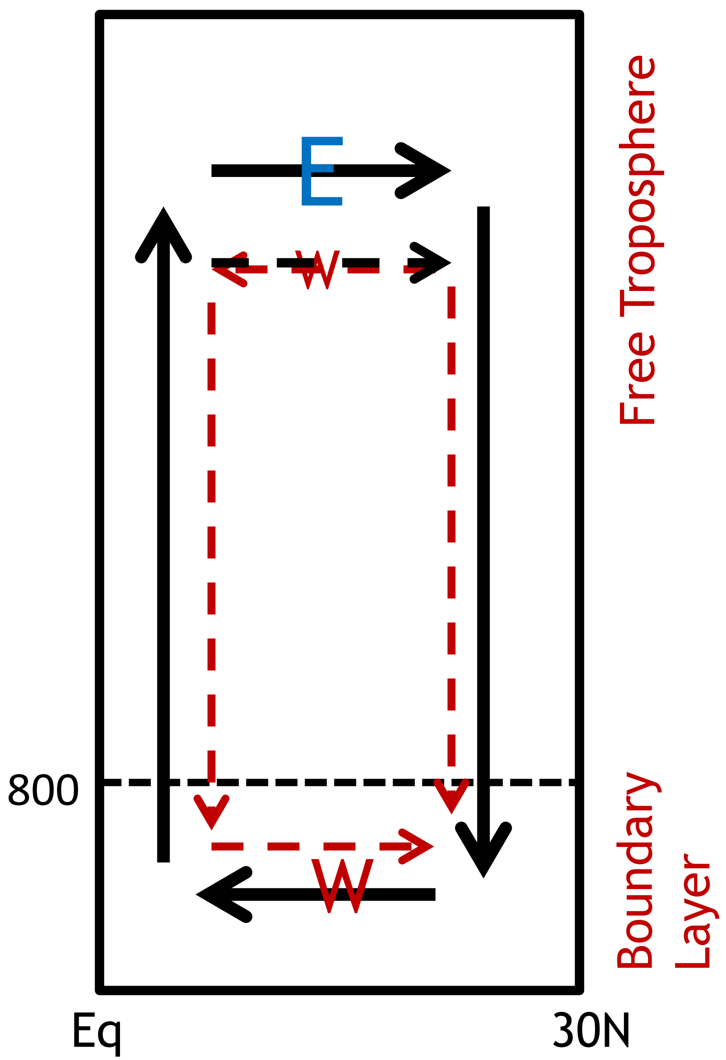
The analysis increments would be expected to…

Local Zonal Momentum Balances



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We'd expect…

An easterly acceleration in the upper troposphere

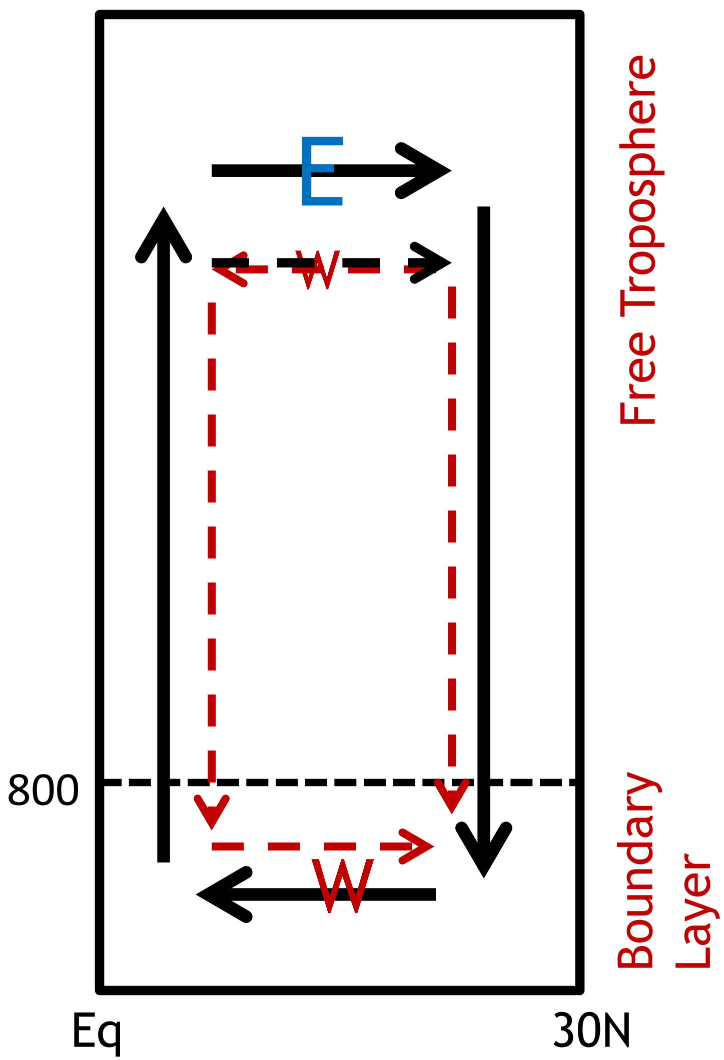
and/or

The upper level Southerlies to strengthen

The analysis increments would be expected to…

Provide a westerly zonal wind anomaly in the upper troposphere

Local Zonal Momentum Balances



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How would we expect things to evolve over the forecast?

We'd expect…

An easterly acceleration in the upper troposphere

and/or

The upper level Southerlies to strengthen

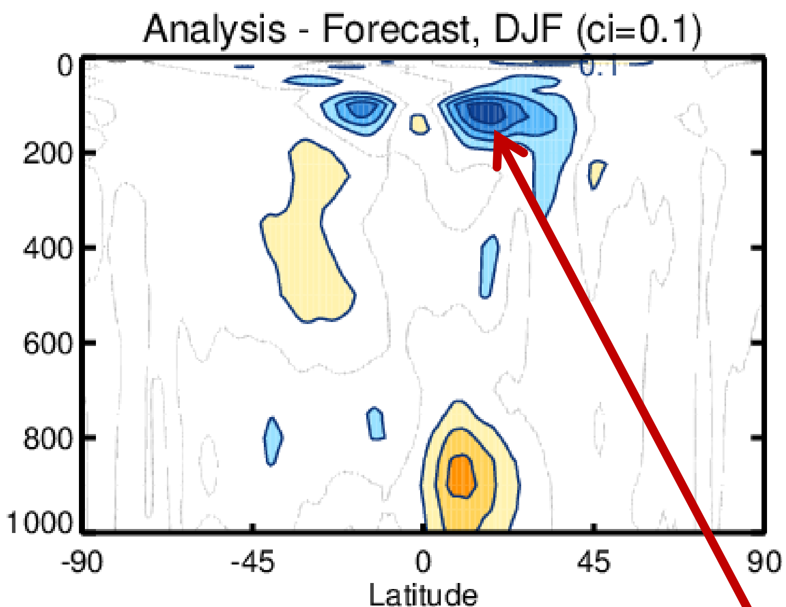
The analysis increments would be expected to…

Provide a westerly zonal wind anomaly in the upper troposphere

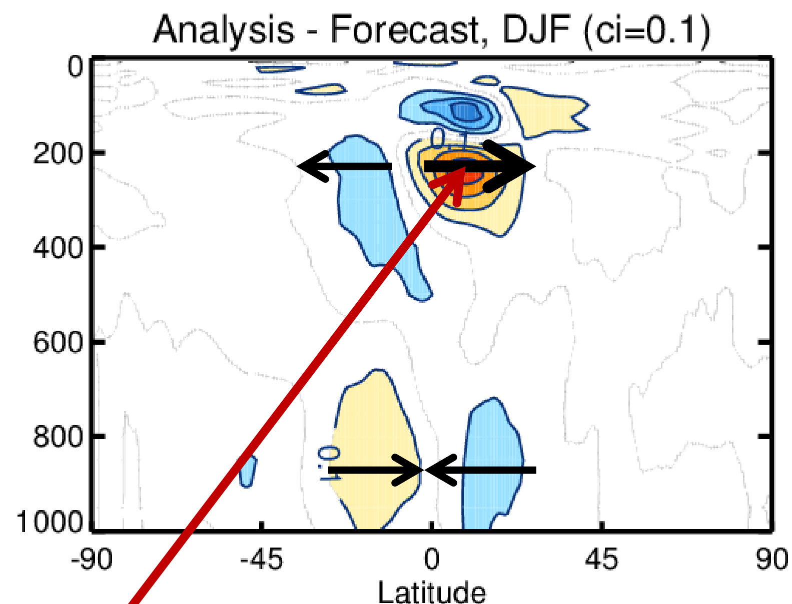
and/or

Weaken the upper level Southerlies

Zonal mean U
(Analysis – Forecast)



Zonal mean V
(Analysis – Forecast)

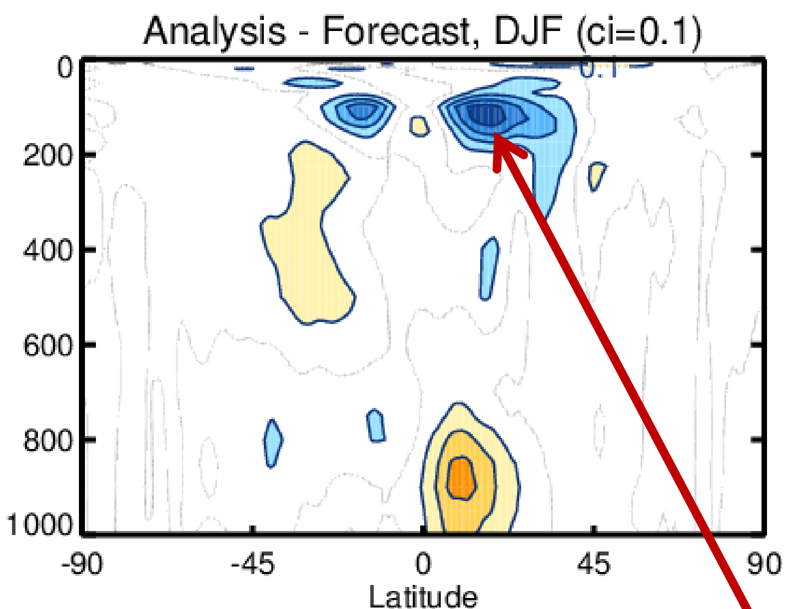


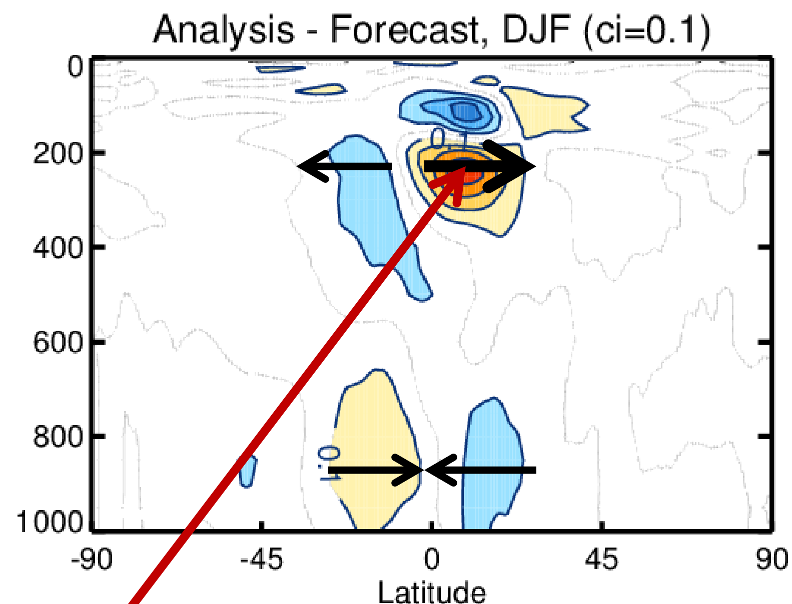
The opposite of what you'd expect in the absence of a westerly forcing in the upper troposphere

The increments are not consistent with the missing westerly forcing being in the upper troposphere

Zo
(Analy

V
cast)





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Zo… (Analy… …V …cast)

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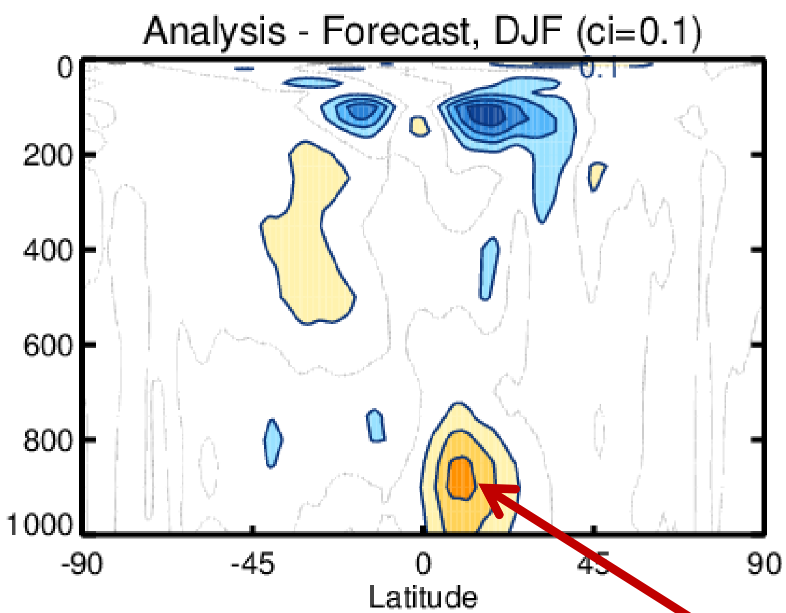
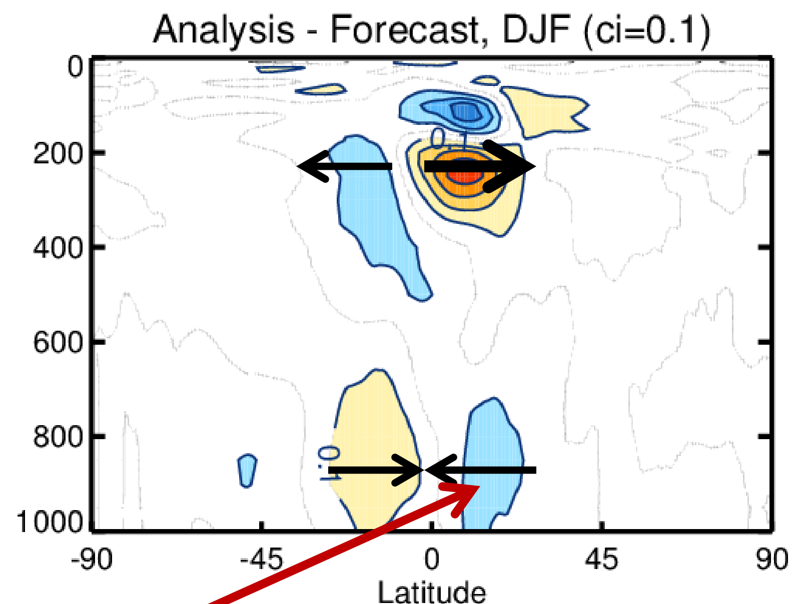




What you'd expect in the absence of a westerly forcing in the lower troposphere

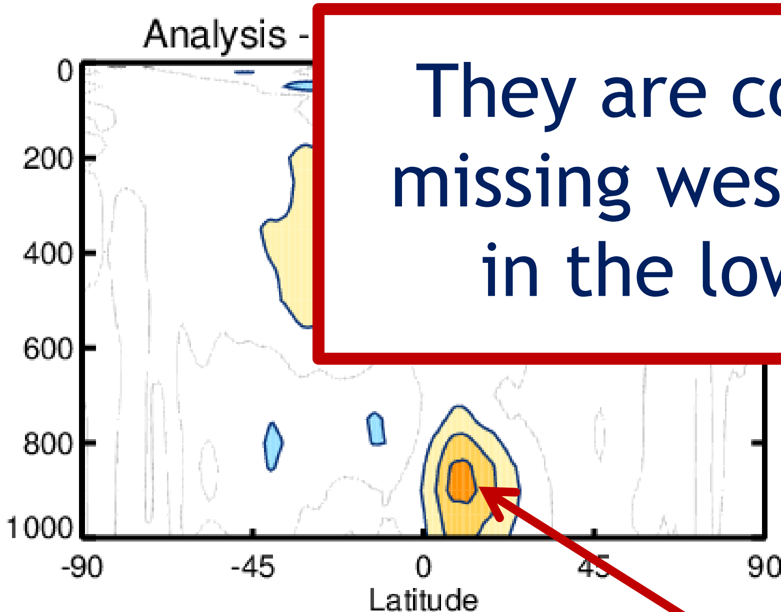
The increments are not consistent with the missing westerly forcing being in the upper troposphere

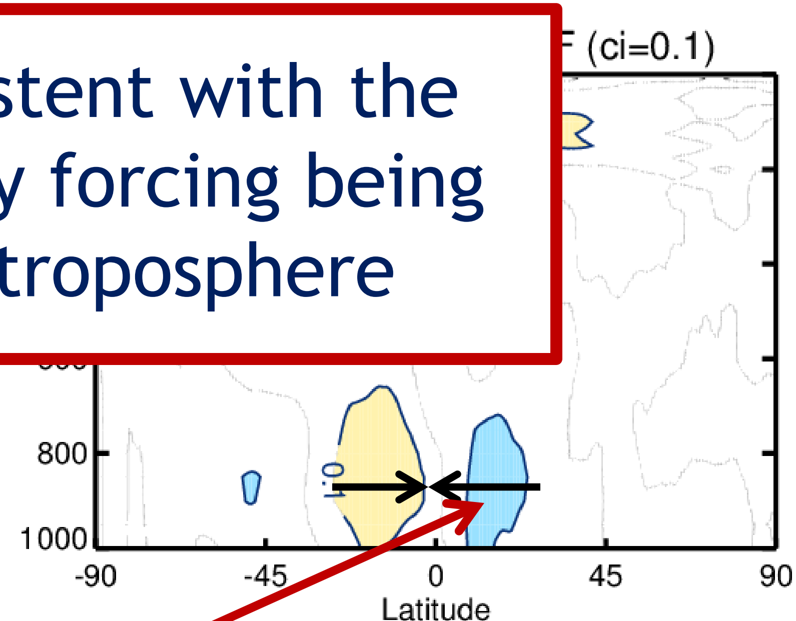
Zo

(Analy

cast)

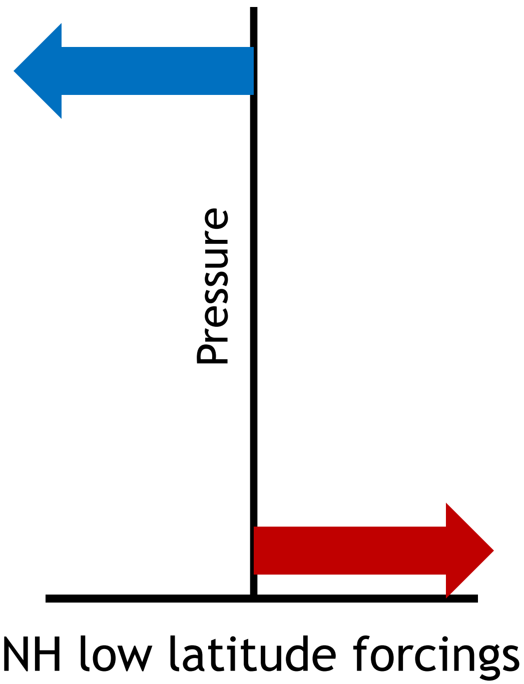
They are consistent with the missing westerly forcing being in the lower troposphere

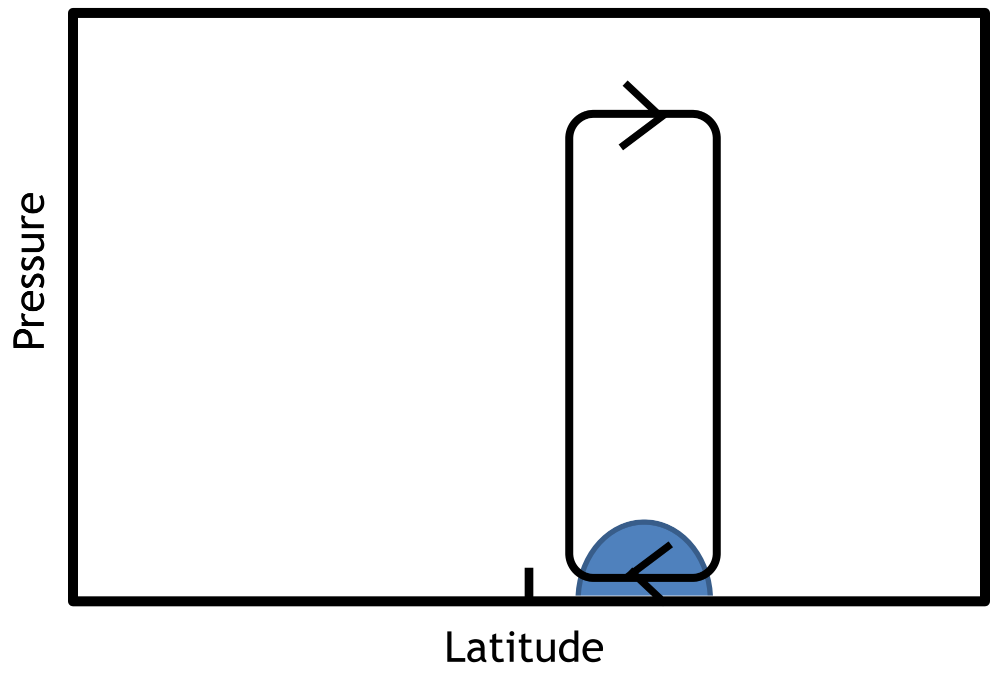




What you’d expect in the absence of a westerly forcing in the lower troposphere

Schematic depiction of the influence of a missing low level westerly tendency in the NH low latitudes





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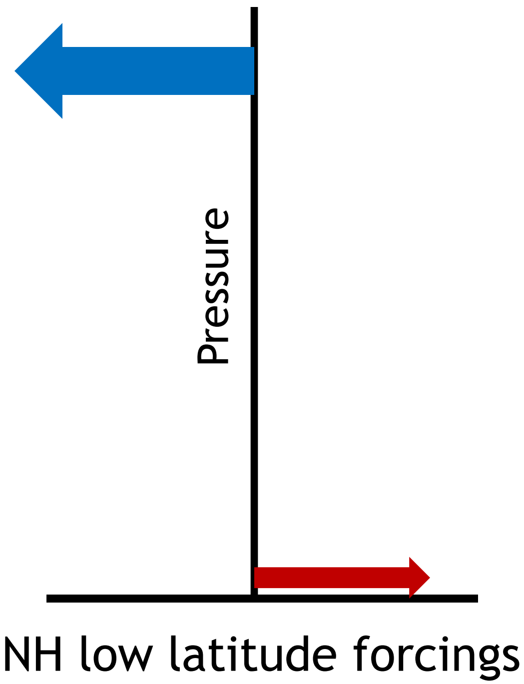

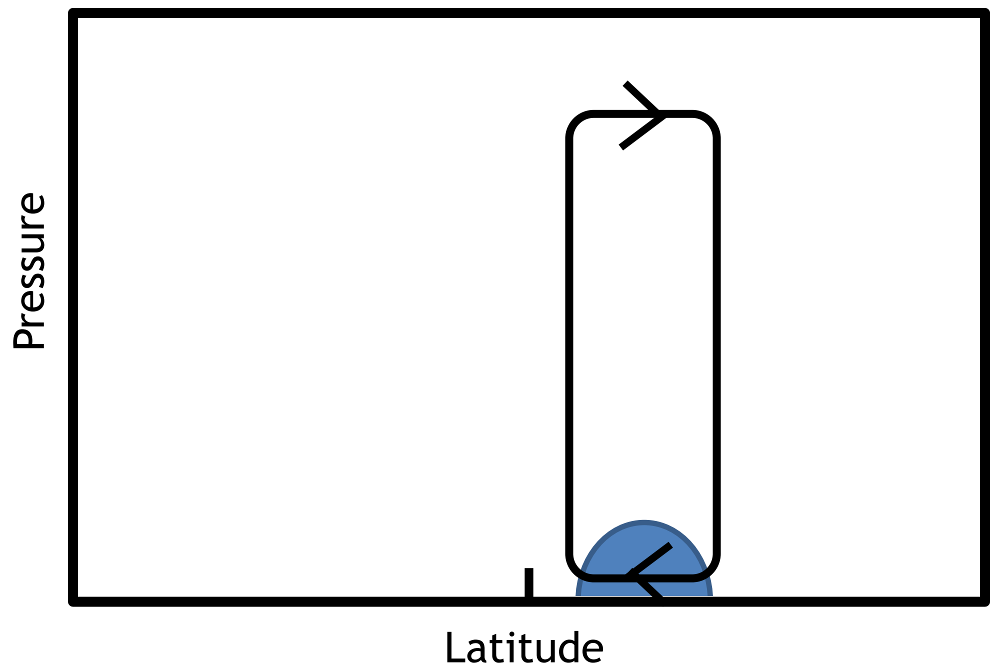

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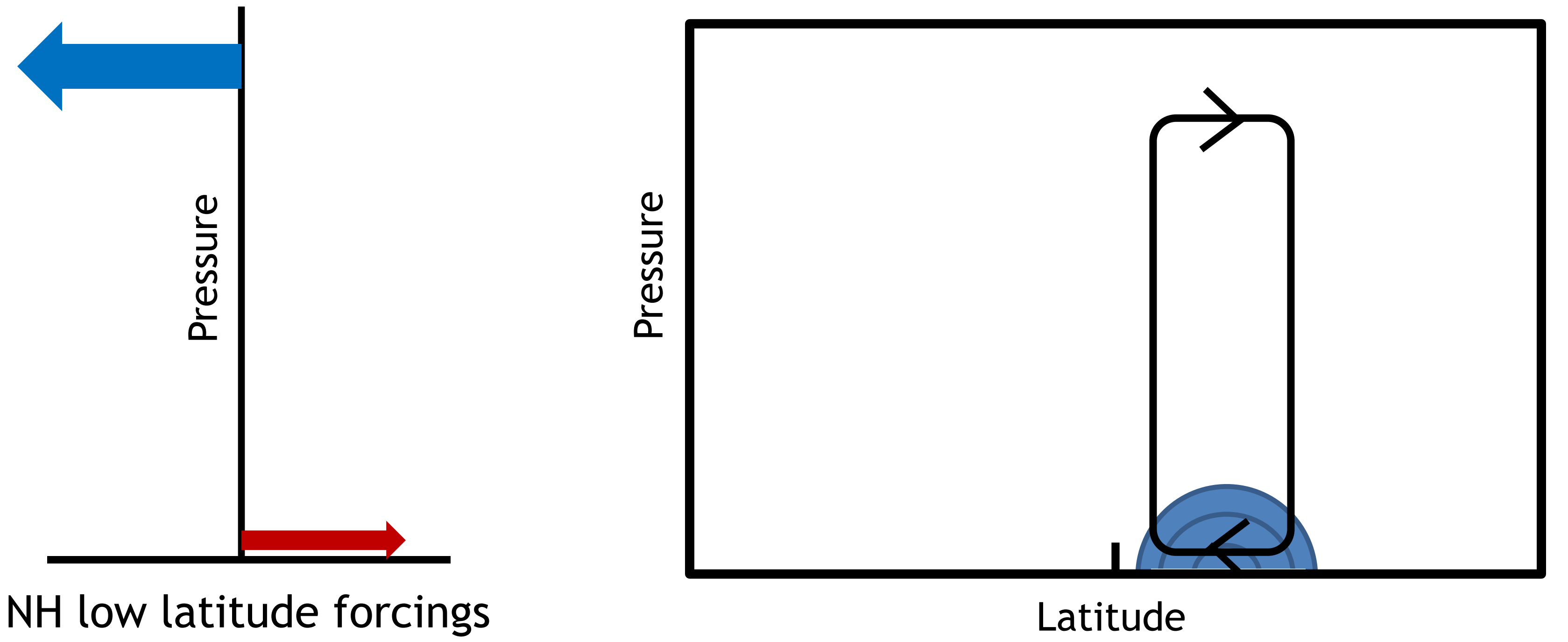

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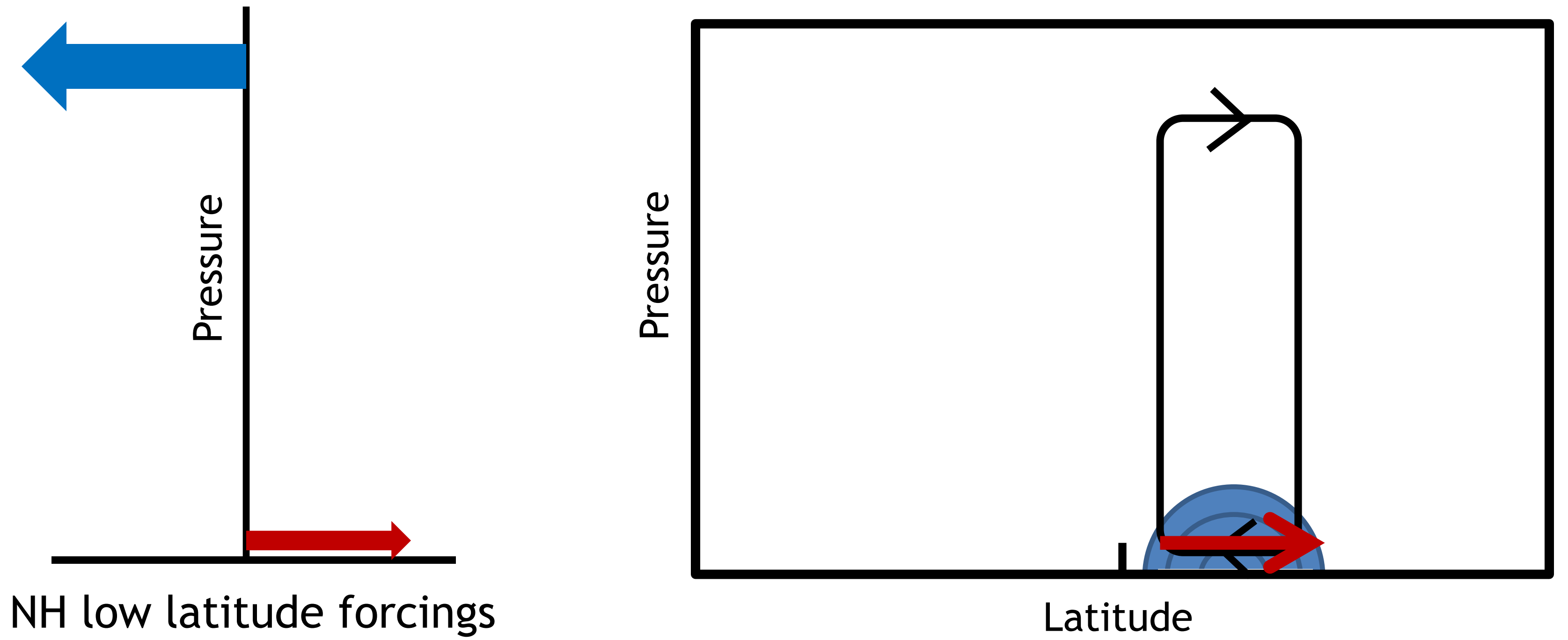

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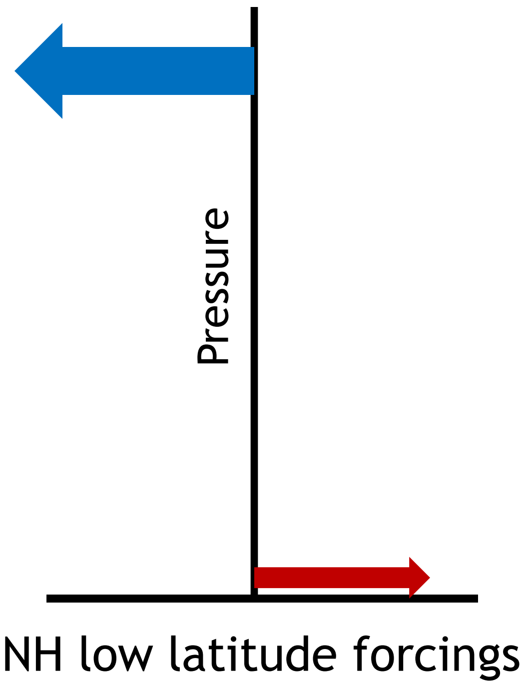

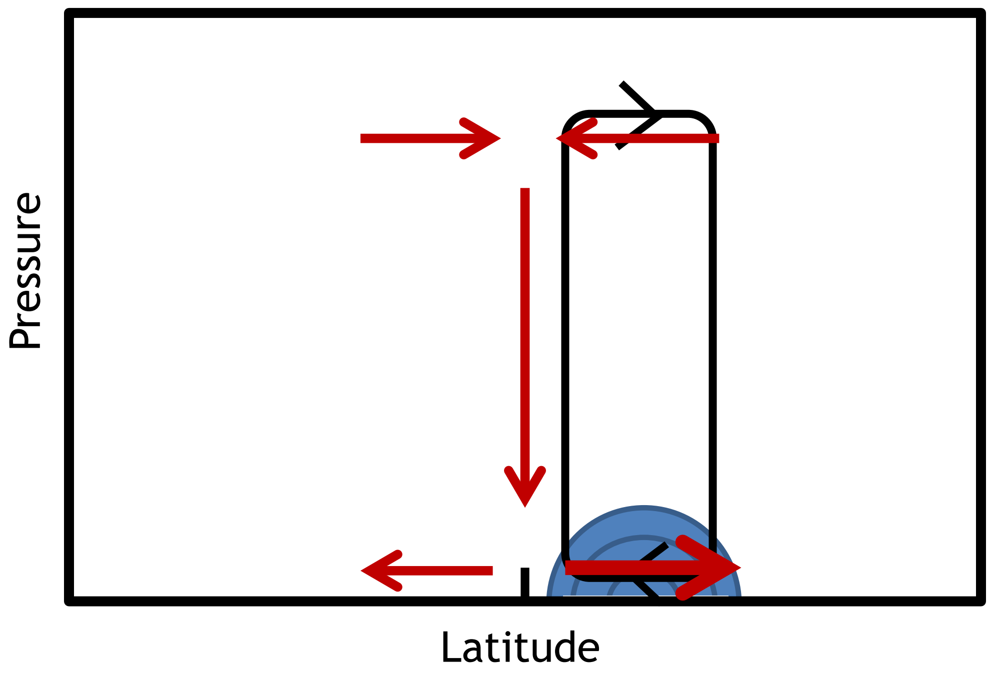

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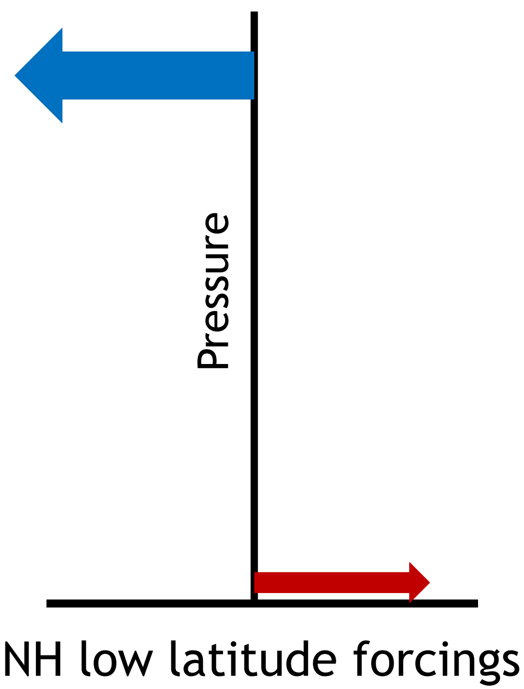

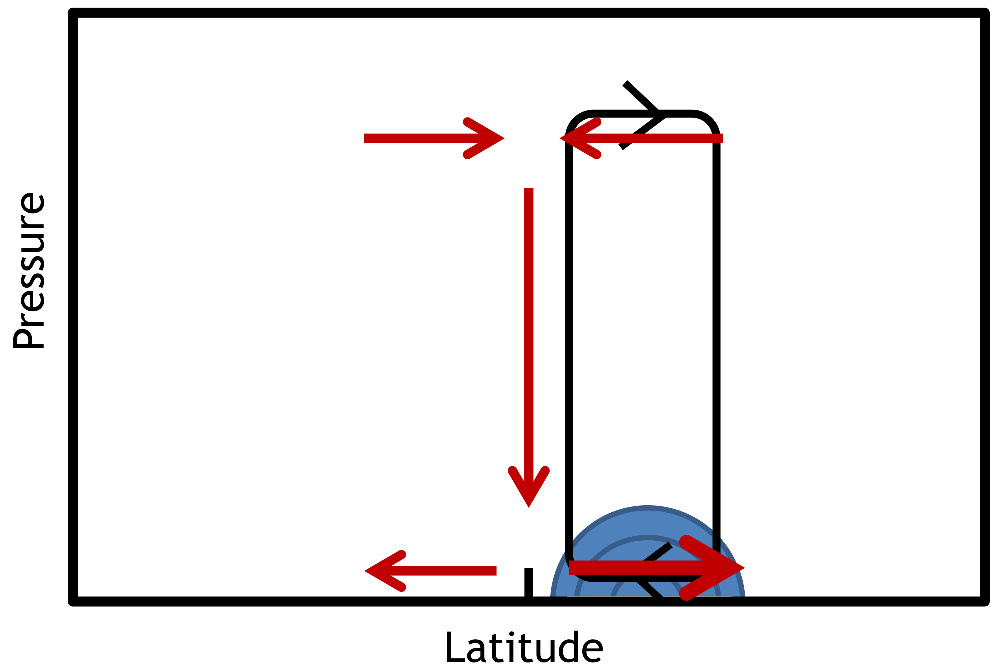

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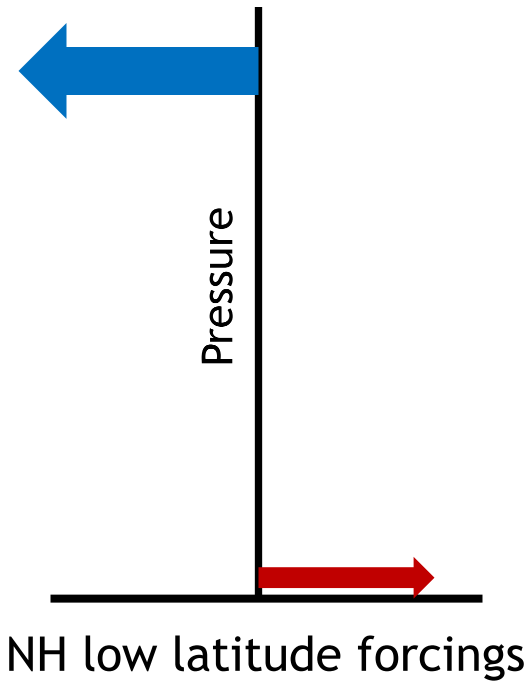
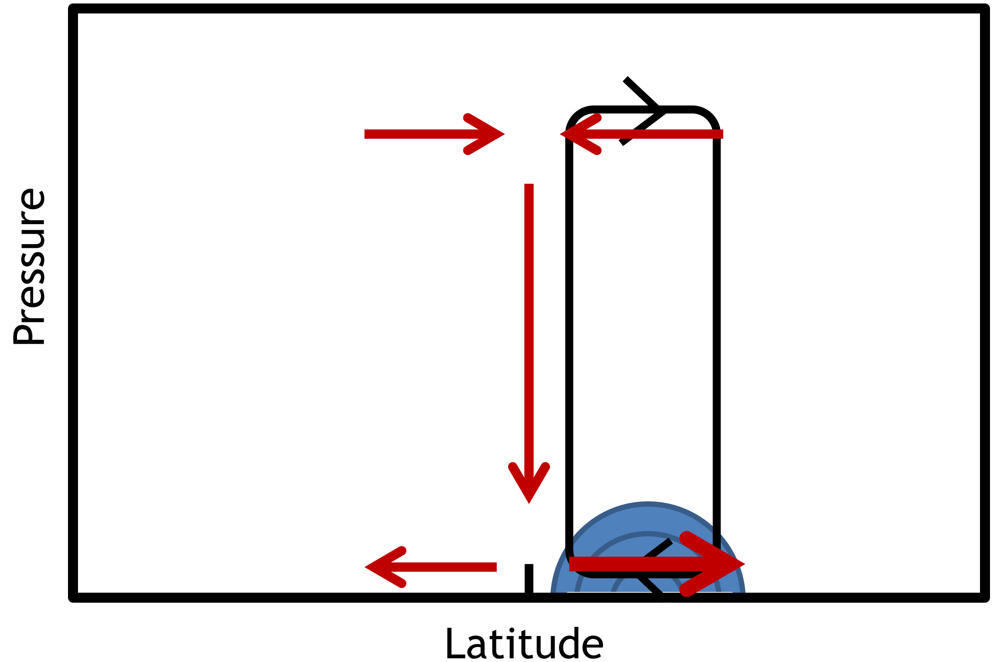
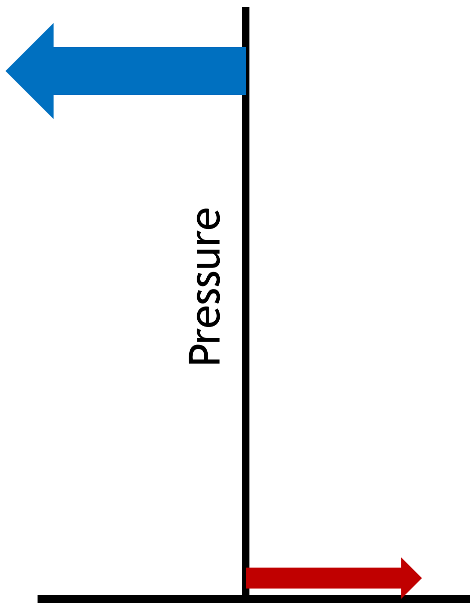


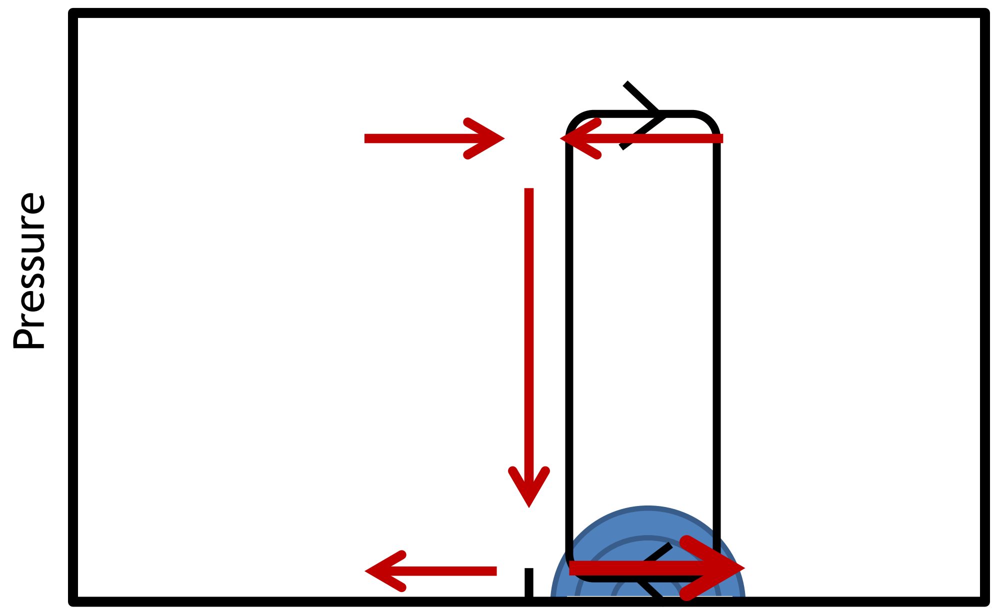


Analysis increments are needed to weaken the low level easterlies and strengthen the Hadley circulation again.

Schematic depiction of the influence of a missing low level westerly tendency in the NH low latitudes



NH low latitude forcings



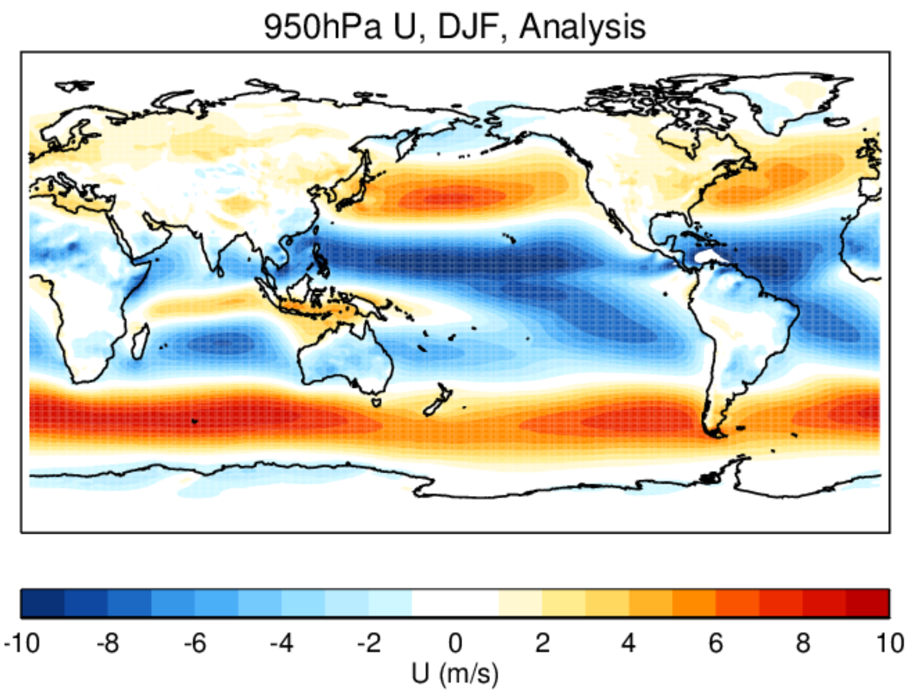
Latitude

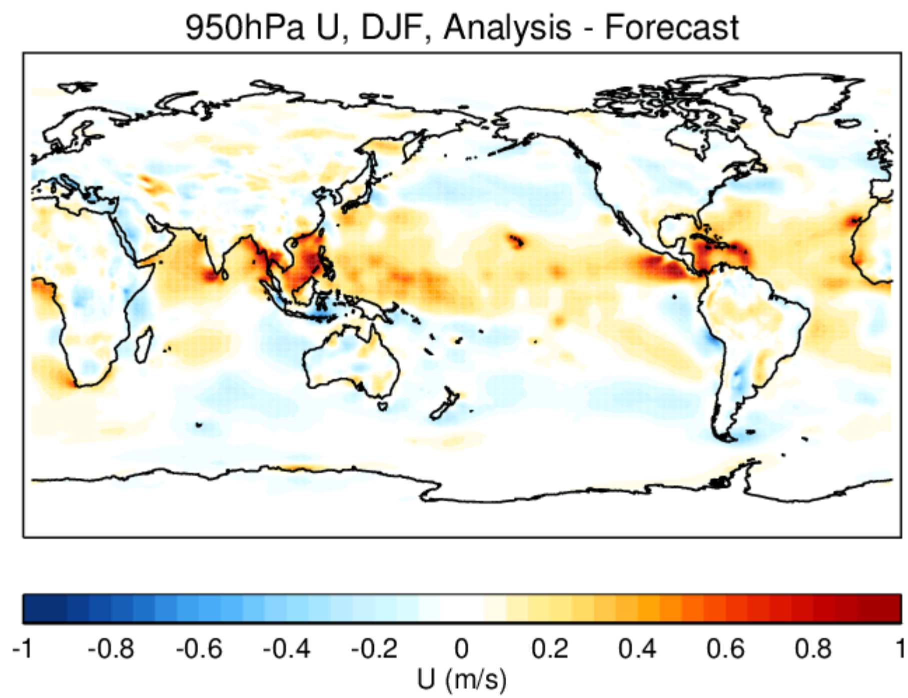
Analysis increments are needed to weaken the low level easterlies and strengthen the Hadley circulation again.

Lat-Lon structure of the analysis increments

Is there something special about the NH low latitudes in winter?

Assimilation acts to reduce the easterly winds in the NH low latitudes almost everywhere. Perhaps more so in regions with observations





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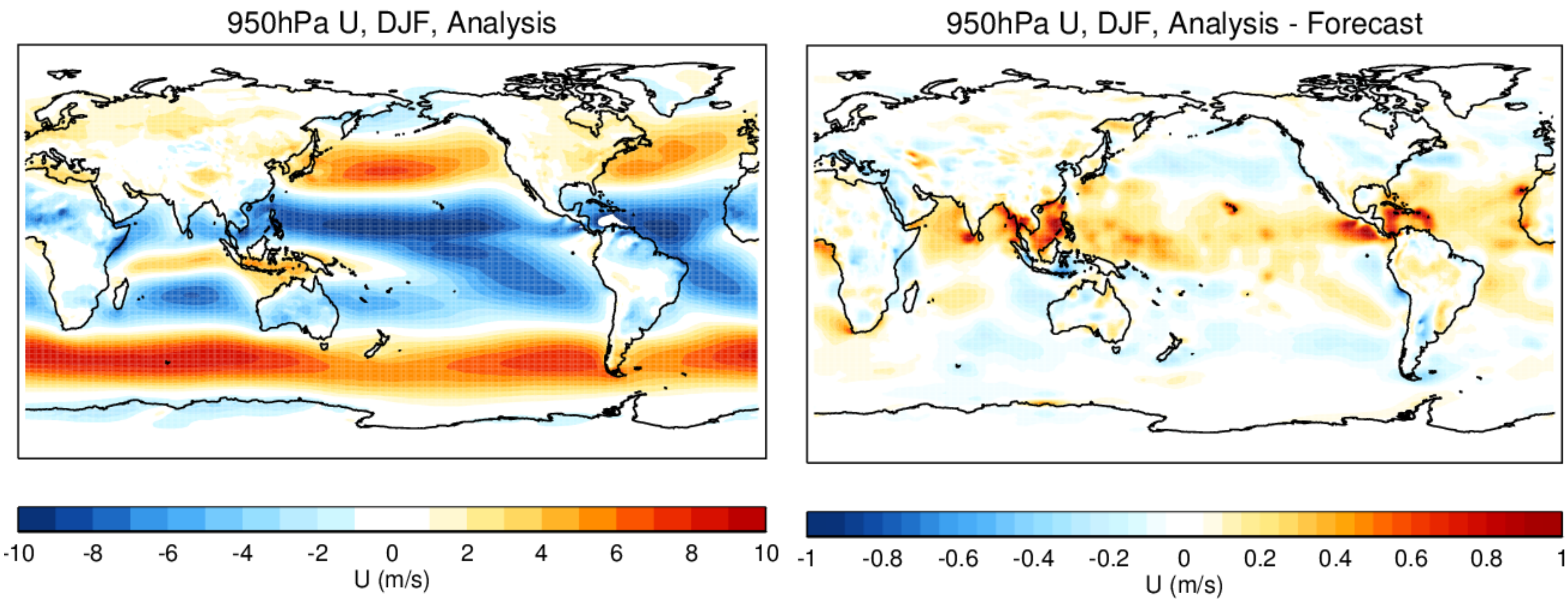

Also a general tendency to oppose the climatological winds in other regions.

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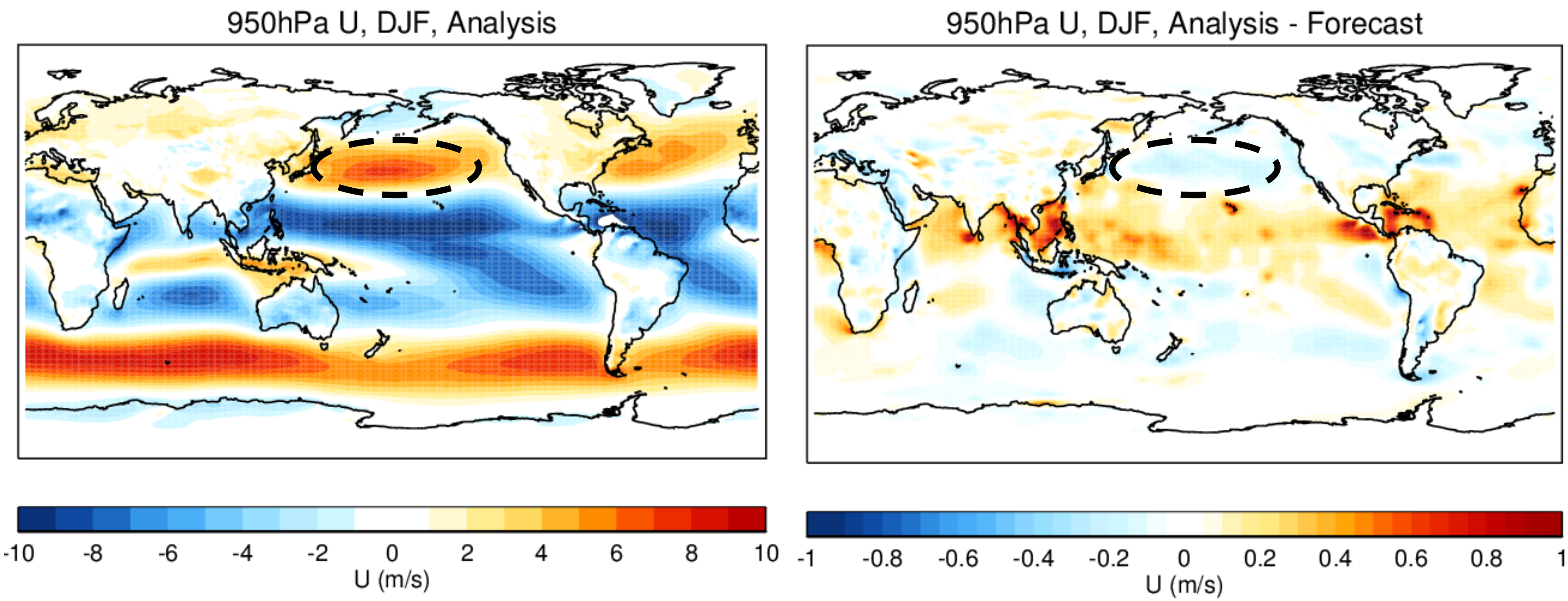

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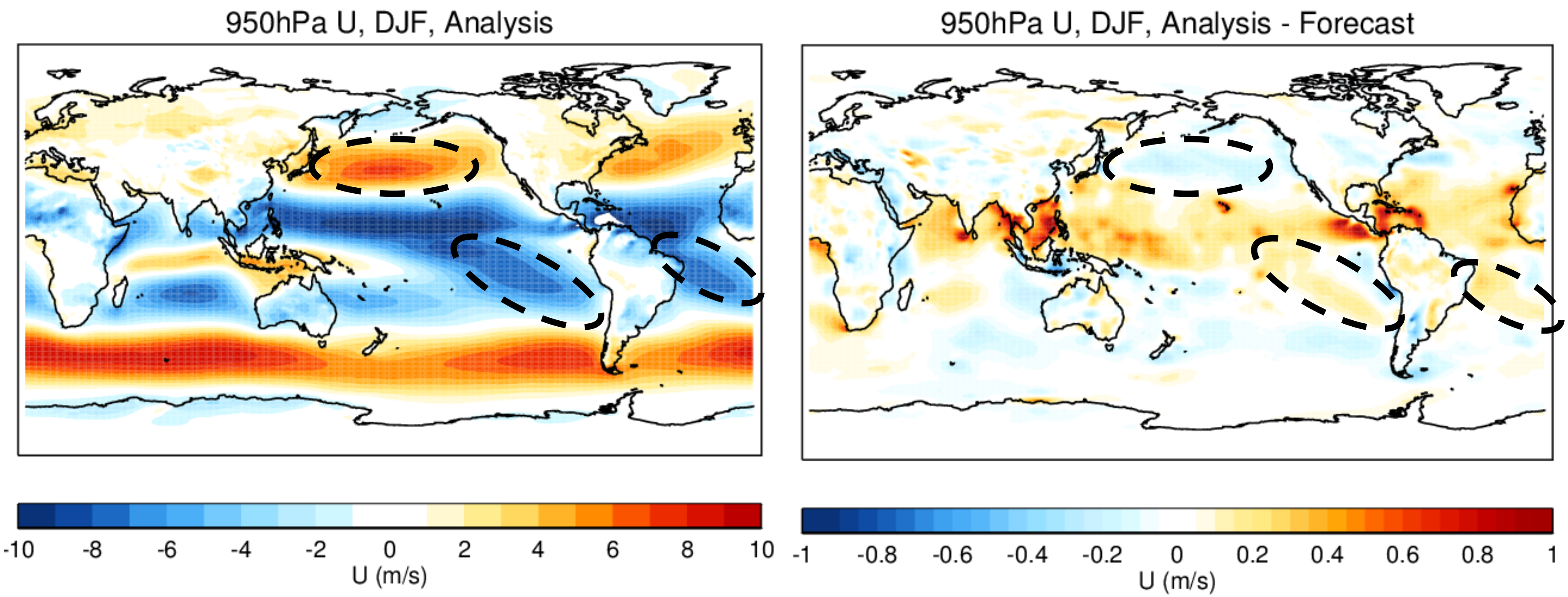

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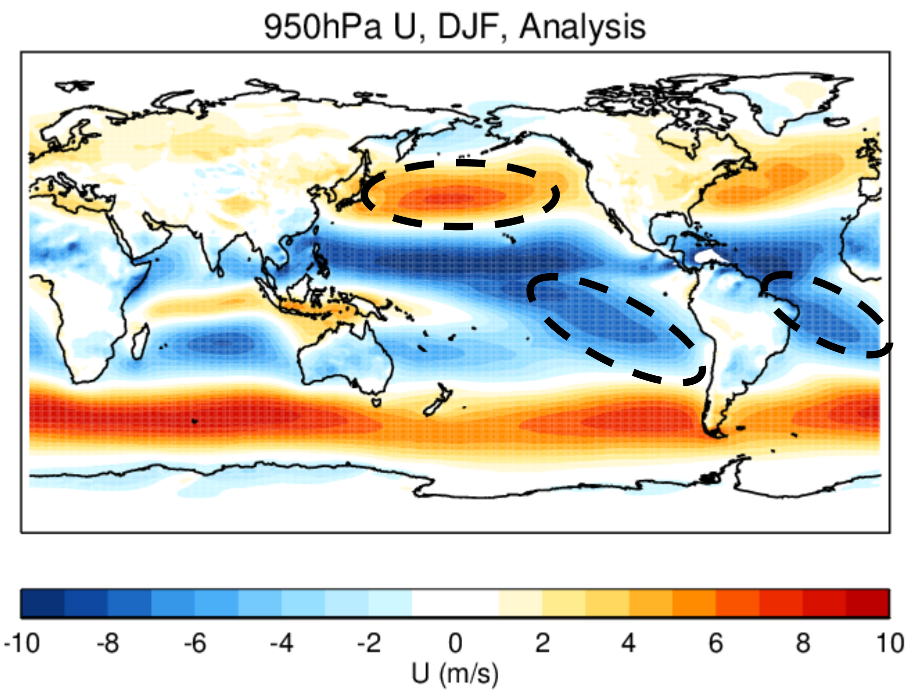
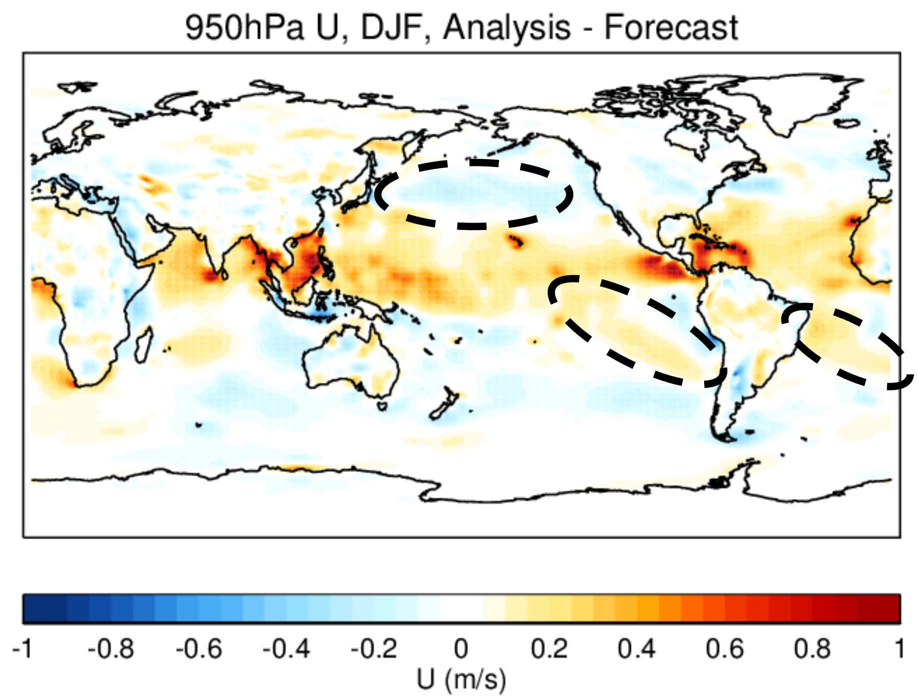
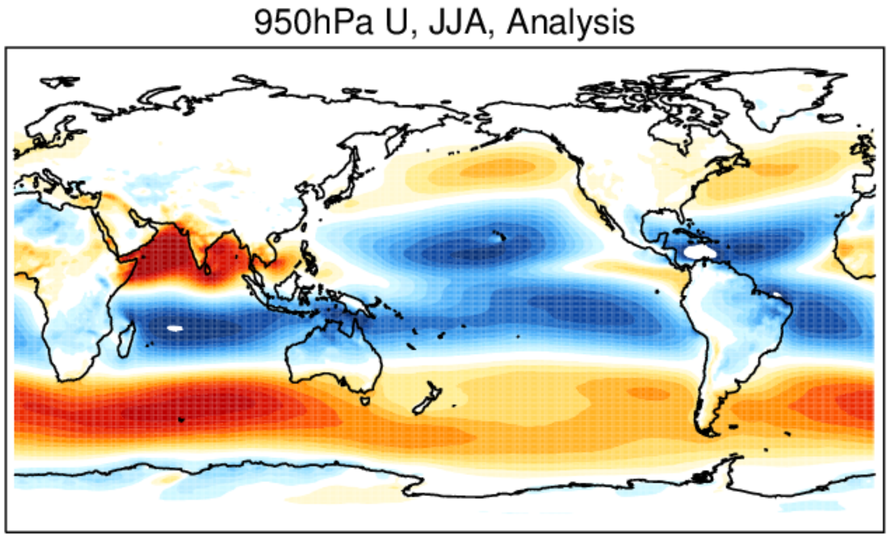


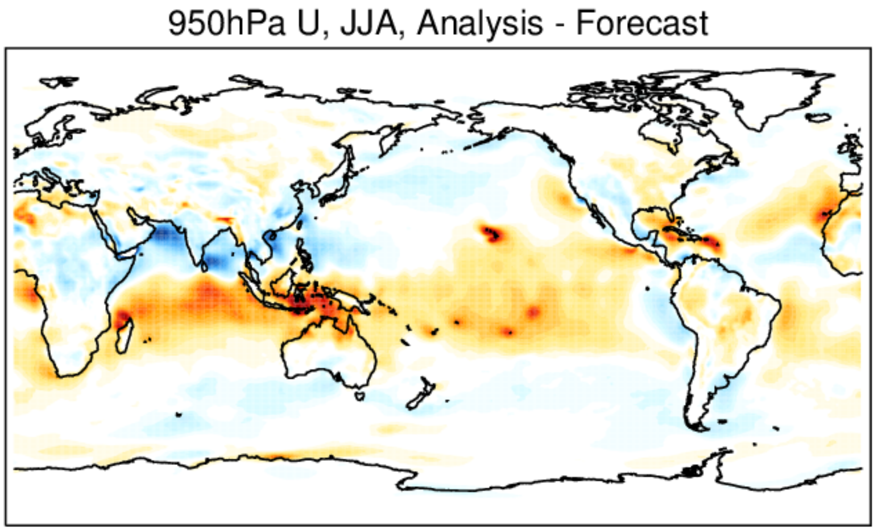


Also a general tendency to oppose the climatological winds in other regions.

But not in the SH higher latitudes, maybe a lack of observations?

What about in JJA?





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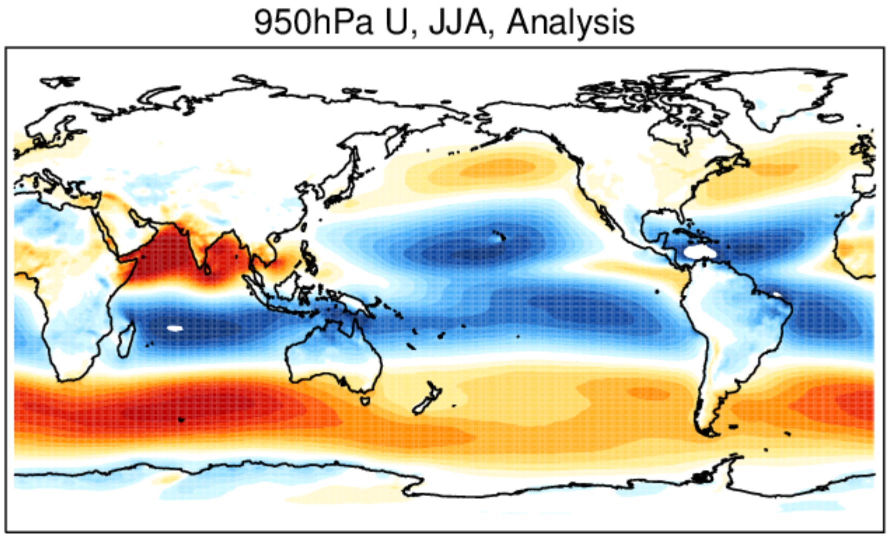

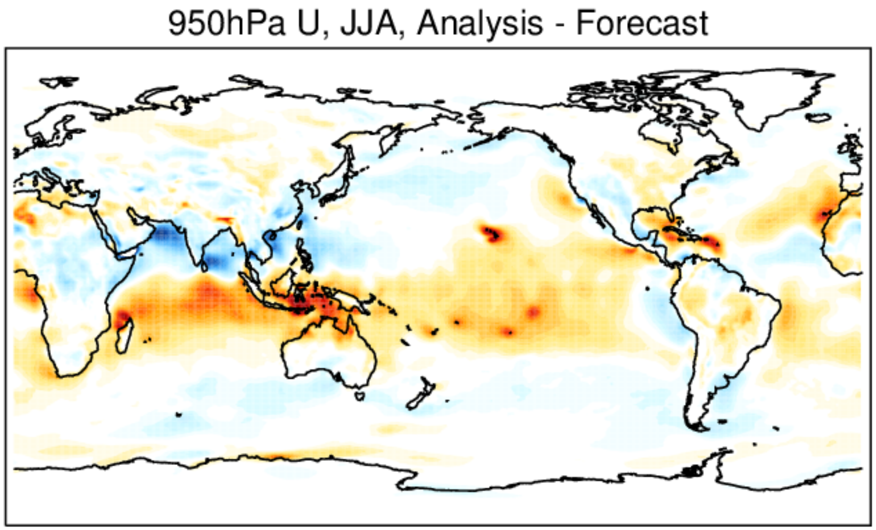

Less zonal symmetry in the NH low latitudes, but still a tendency for the increments to oppose the climatological flow.

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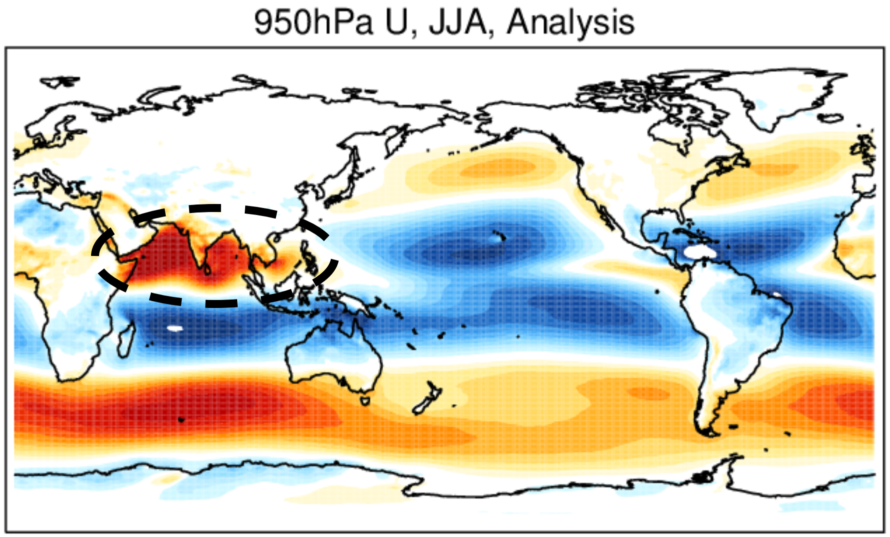

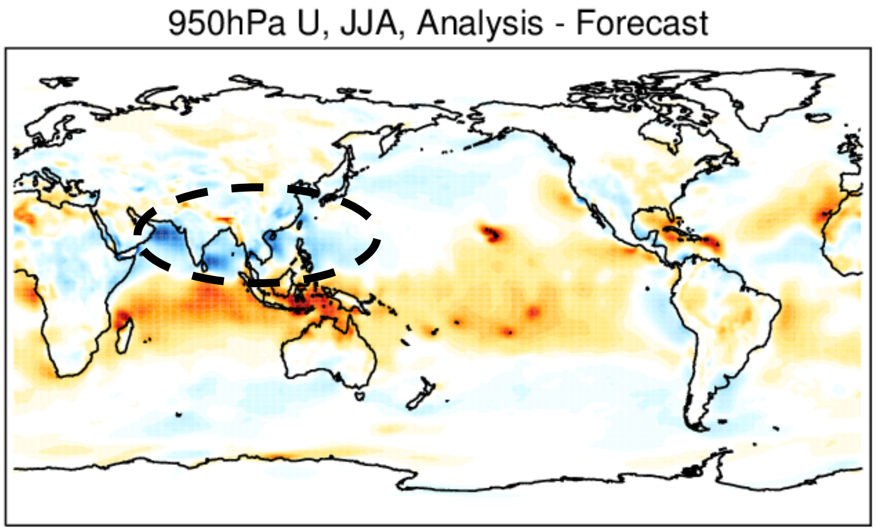

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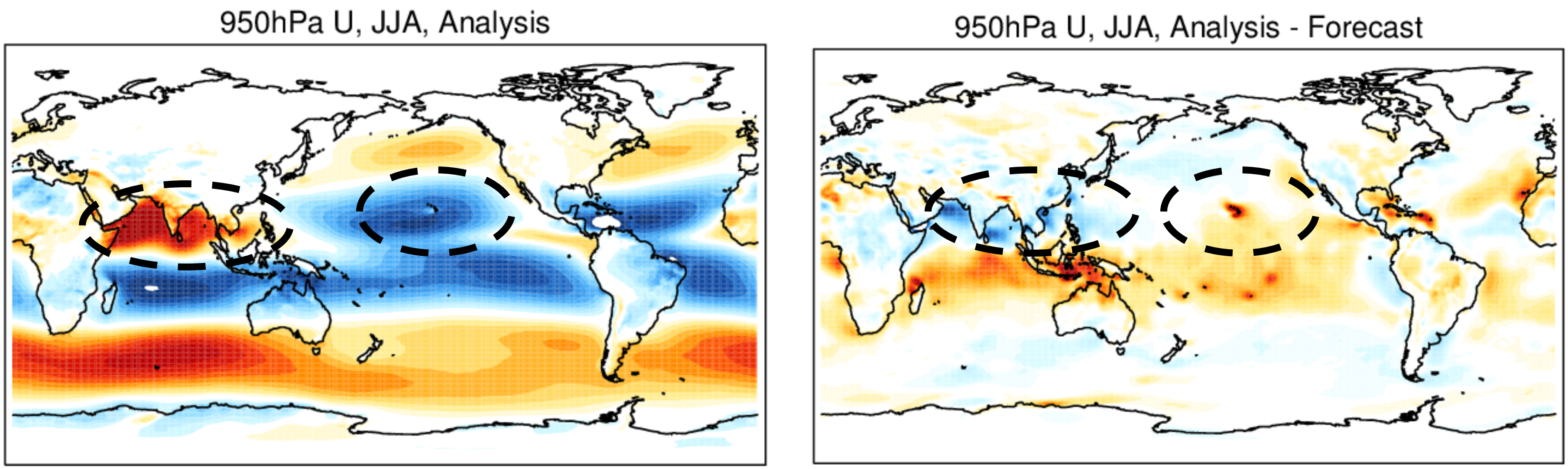

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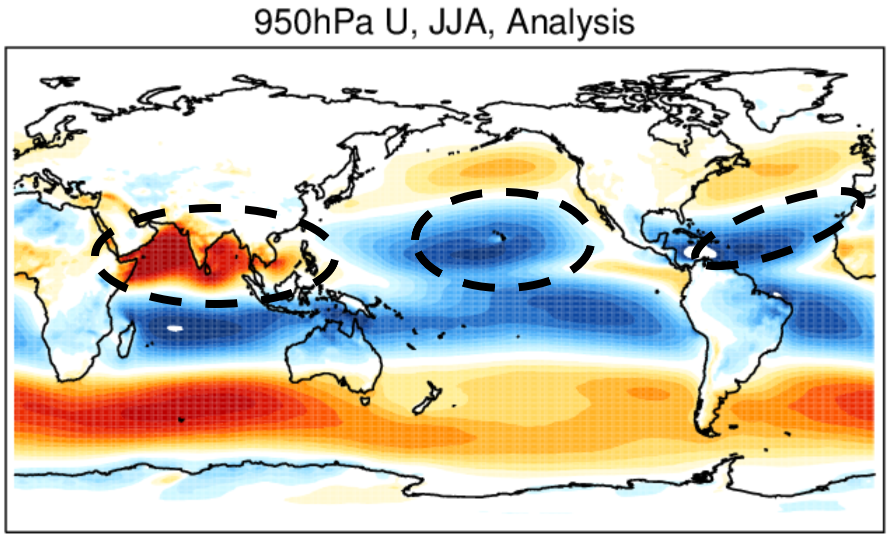

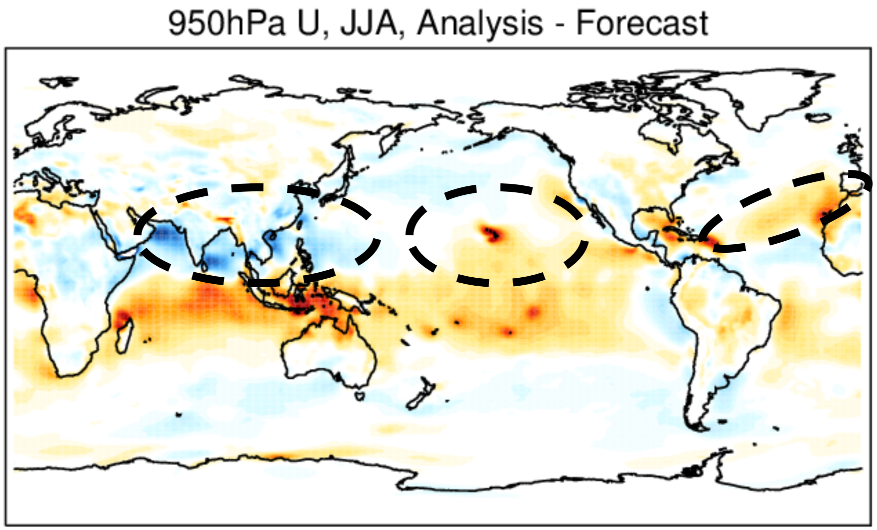

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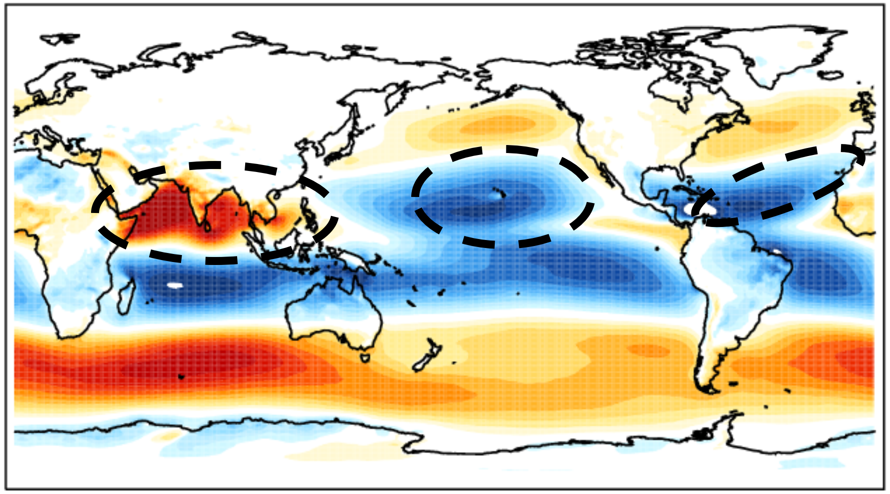
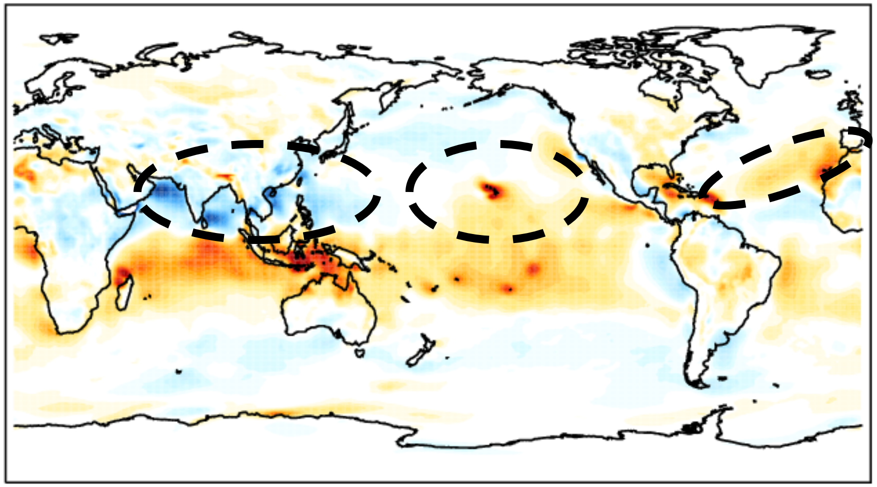
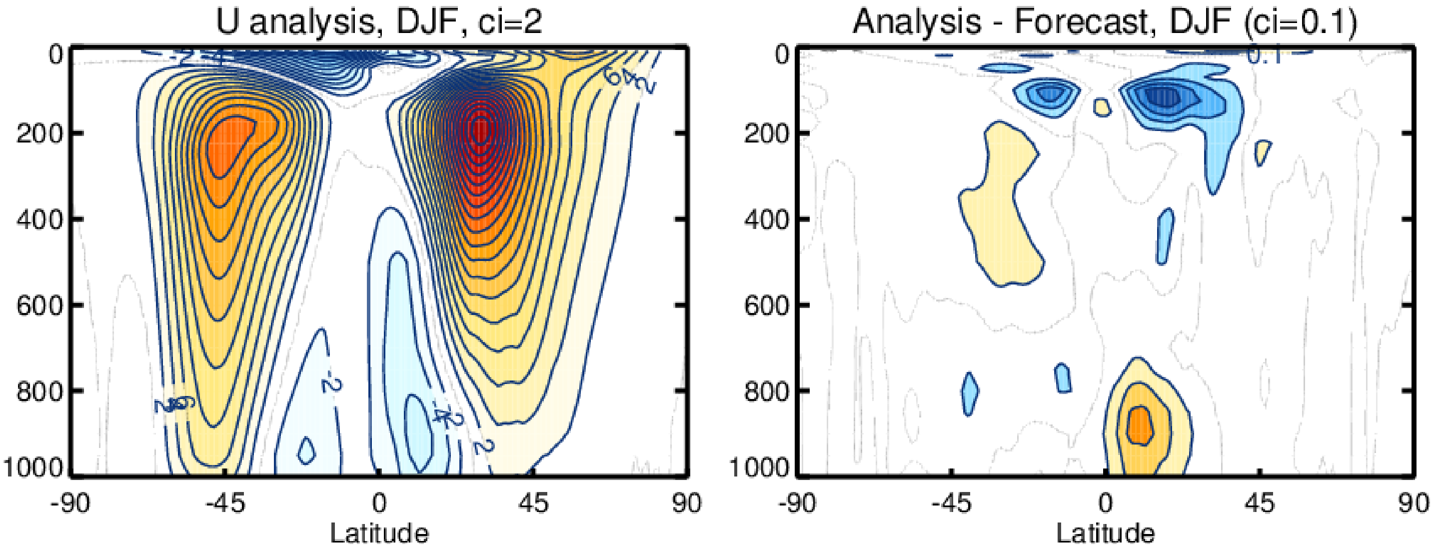




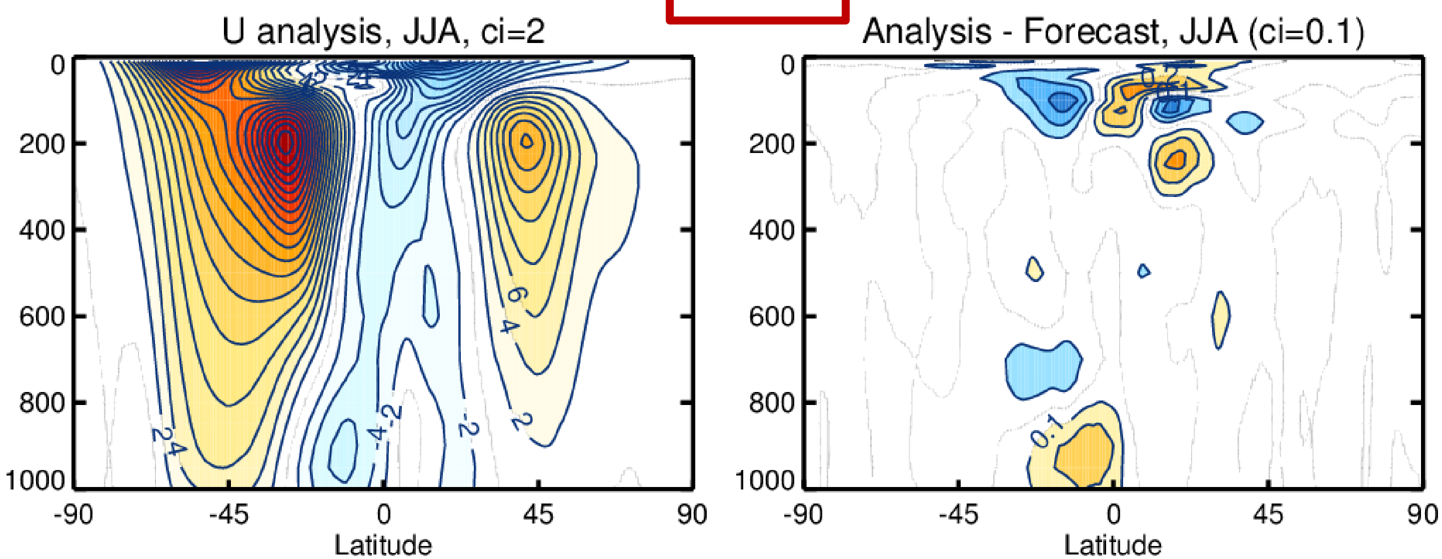
Less zonal symmetry in the NH low latitudes, but still a tendency for the increments to oppose the climatological flow.

Increments oppose the SH zonally symmetric low latitude easterlies.

DJF


U analysis, DJF, ci=2
Analysis - Forecast, DJF (ci=0.1)
0
200
400
600
800
1000
-90
-45
0
45
90
Latitude

JJA


U analysis, JJA, ci=2
Analysis - Forecast, JJA (ci=0.1)
0
200
400
600
800
1000
-90
-45
0
45
90
Latitude

Lat-Lon structure of the analysis increments

Is there something special about the NH low latitudes in winter?

No, the increments act to oppose the low level flow in general.

Two Possibilities?

(1) An incorrect formulation of the surface drag. Should have a stronger surface drag for a given low level flow.

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This would mean that the surface drag output from the reanalysis is incorrect. It should be more easterly in the NH low latitudes.

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This would mean that the surface drag output from the reanalysis is incorrect. It should be more easterly in the NH low latitudes.

The surface drag in the CMIP models would be more correct, but they're getting it for the wrong reasons. They're getting it with a low level flow that's too strong.

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Then the near surface winds and the surface wind stress from the reanalysis would be correct.

We're just compensating for this missing process with the analysis increments.

In that case, both the near surface winds and the surface drag in the CMIP models would be incorrect.

All (?) global estimates of surface stress rely on assumptions about the drag coefficient.

$$\tau = \rho C_D \vec{v}_{10} |\vec{v}_{10}|$$

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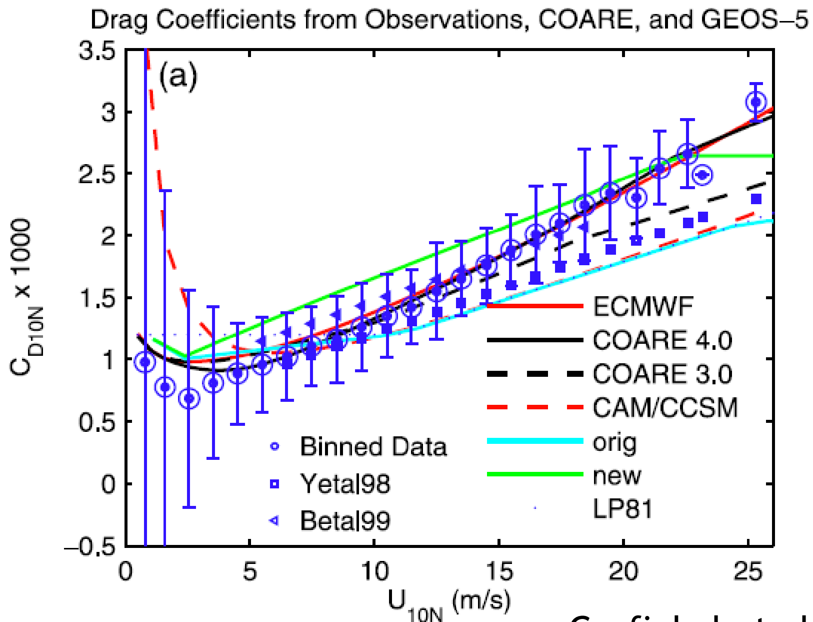
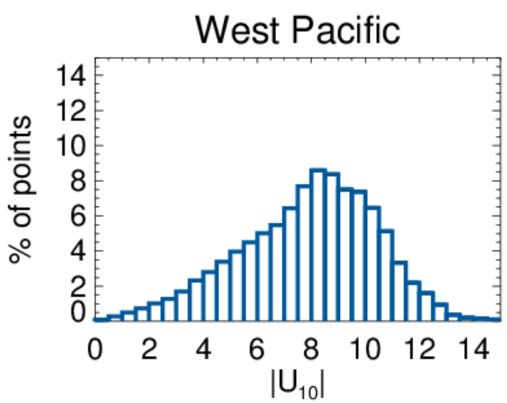
$$\tau = \rho C_D \vec{v}_{10} |\vec{v}_{10}|$$

How confident are we in the drag coefficient?



Garfinkel et al (2011)



Instantaneous 10m wind magnitudes

All (?) global estimates of surface stress rely on assumptions about the drag coefficient.

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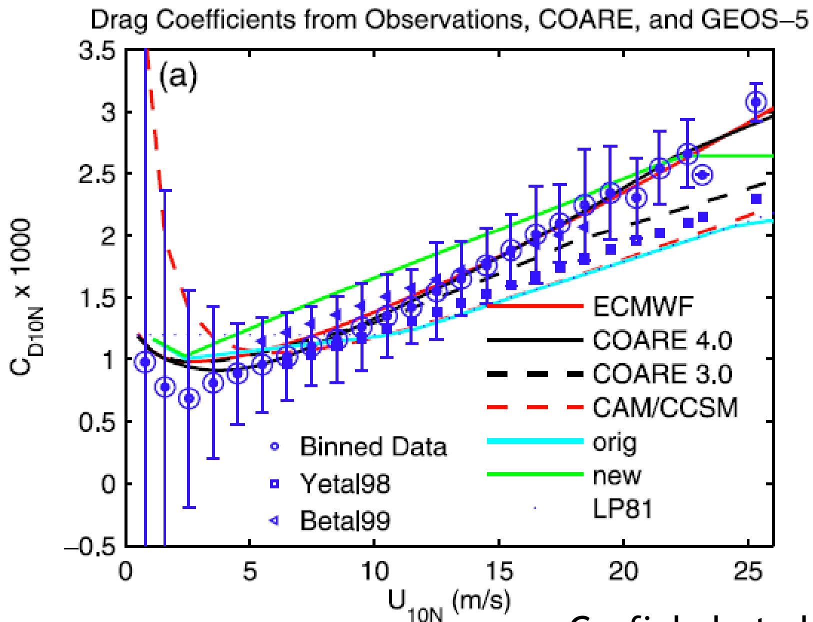
How confident are we in the drag coefficient?

Or do we need to explain the missing low level tendencies with some other physics?



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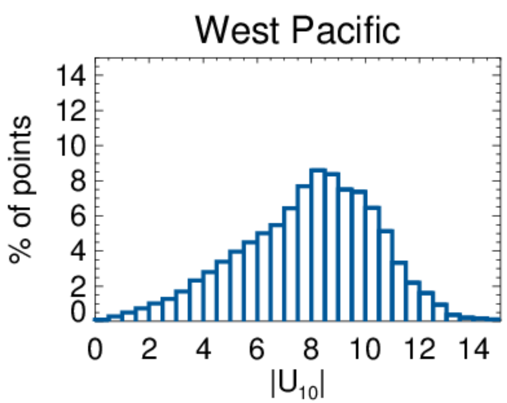
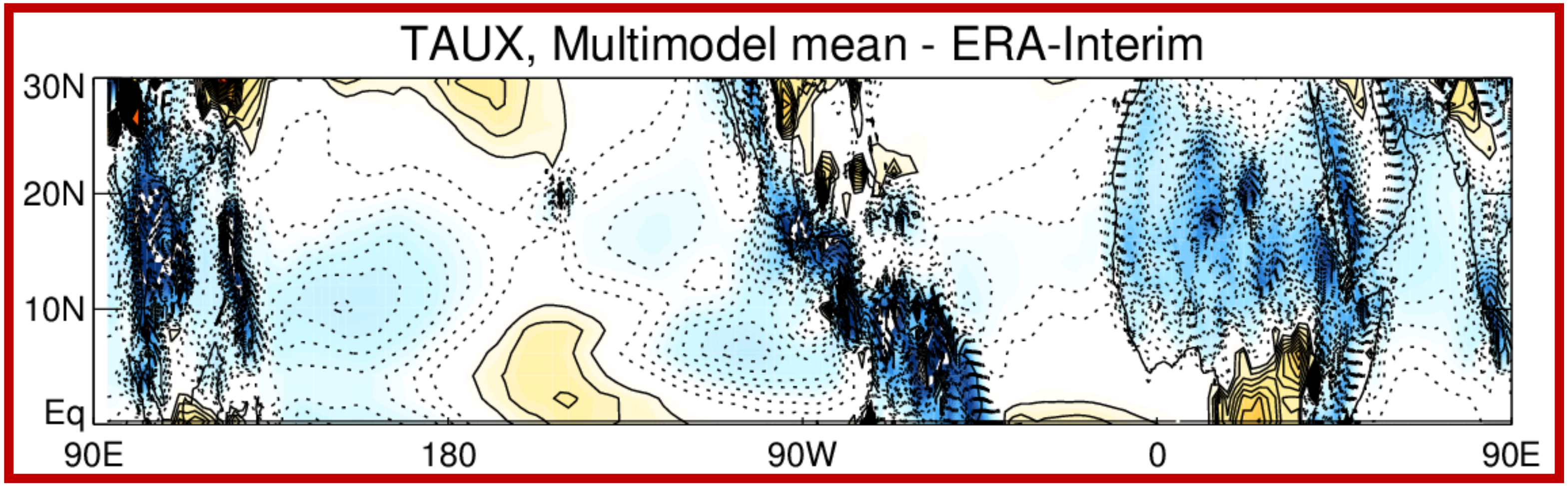


Instantaneous 10m wind magnitudes

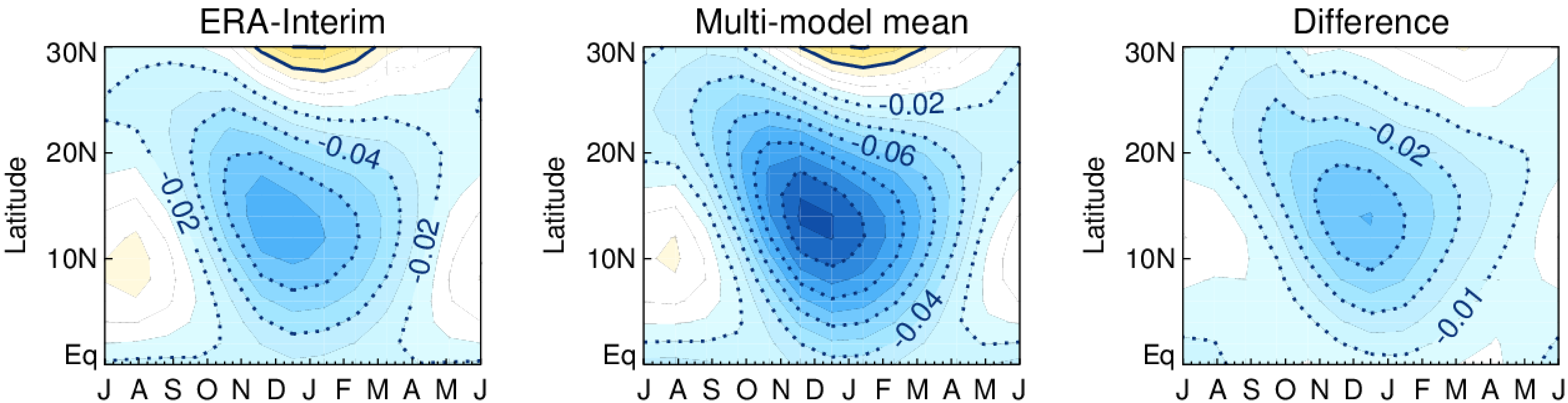
Thanks!

Extra Slides

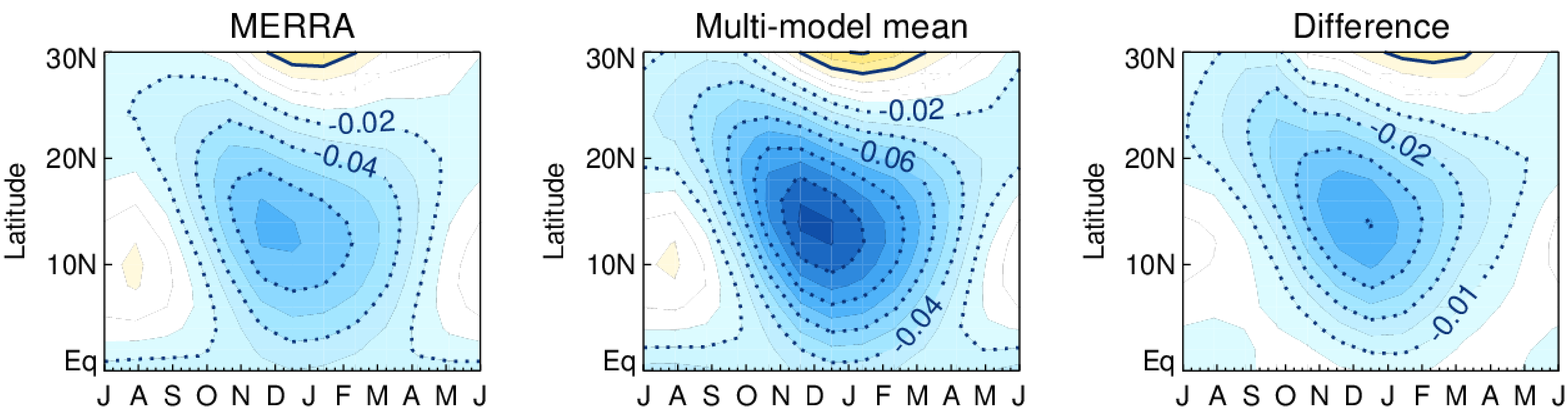

TAUX, Multimodel mean - ERA-Interim
30N
20N
10N
Eq
90E
180
90W
0
90E

Seasonal evolution of low latitude wind stress differences

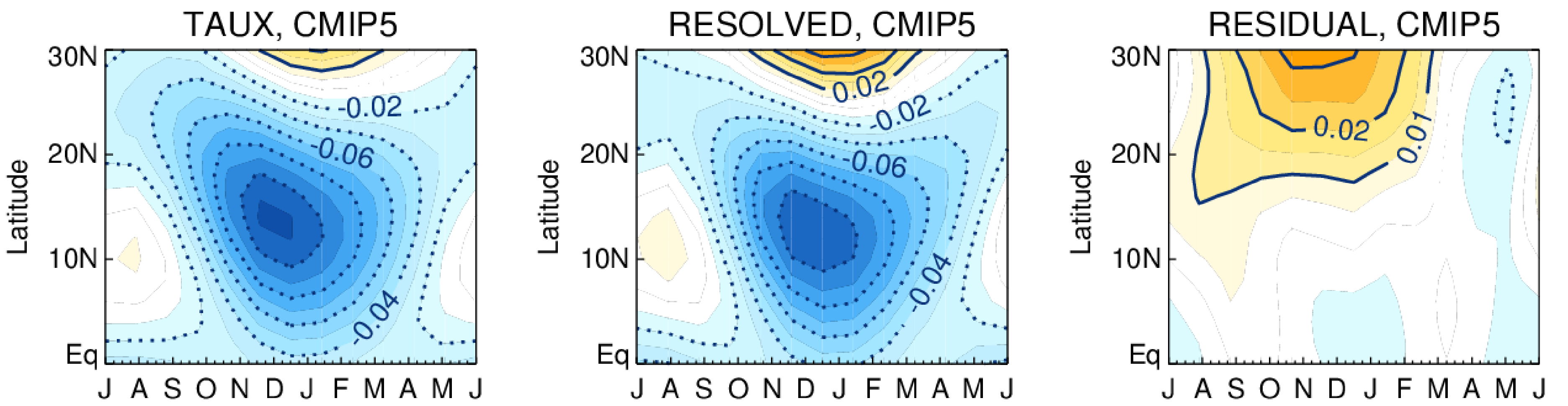
ERA-Interim vs multi-model mean



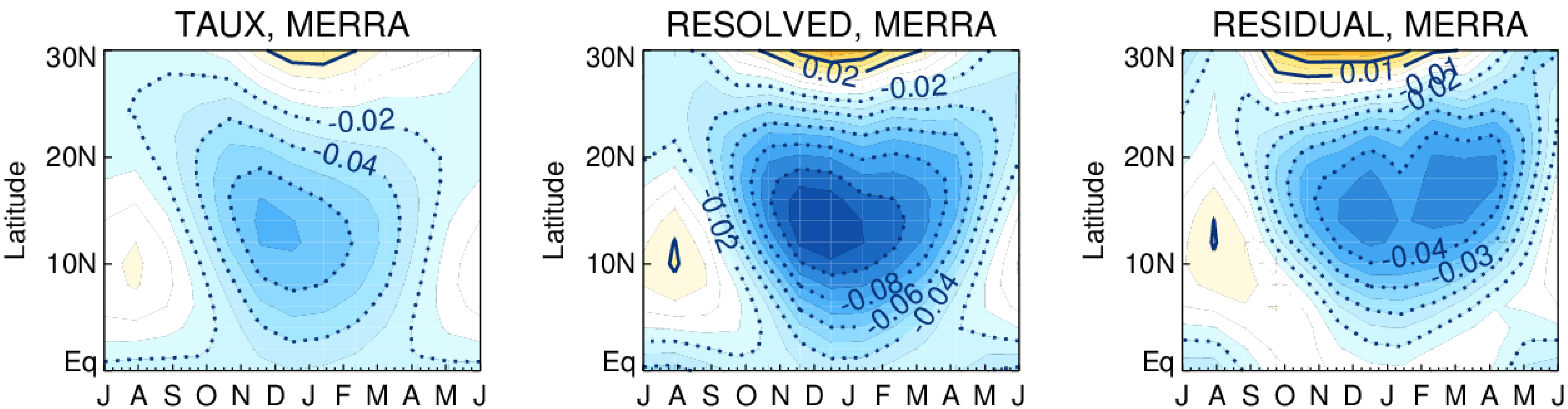
MERRA vs multi-model mean



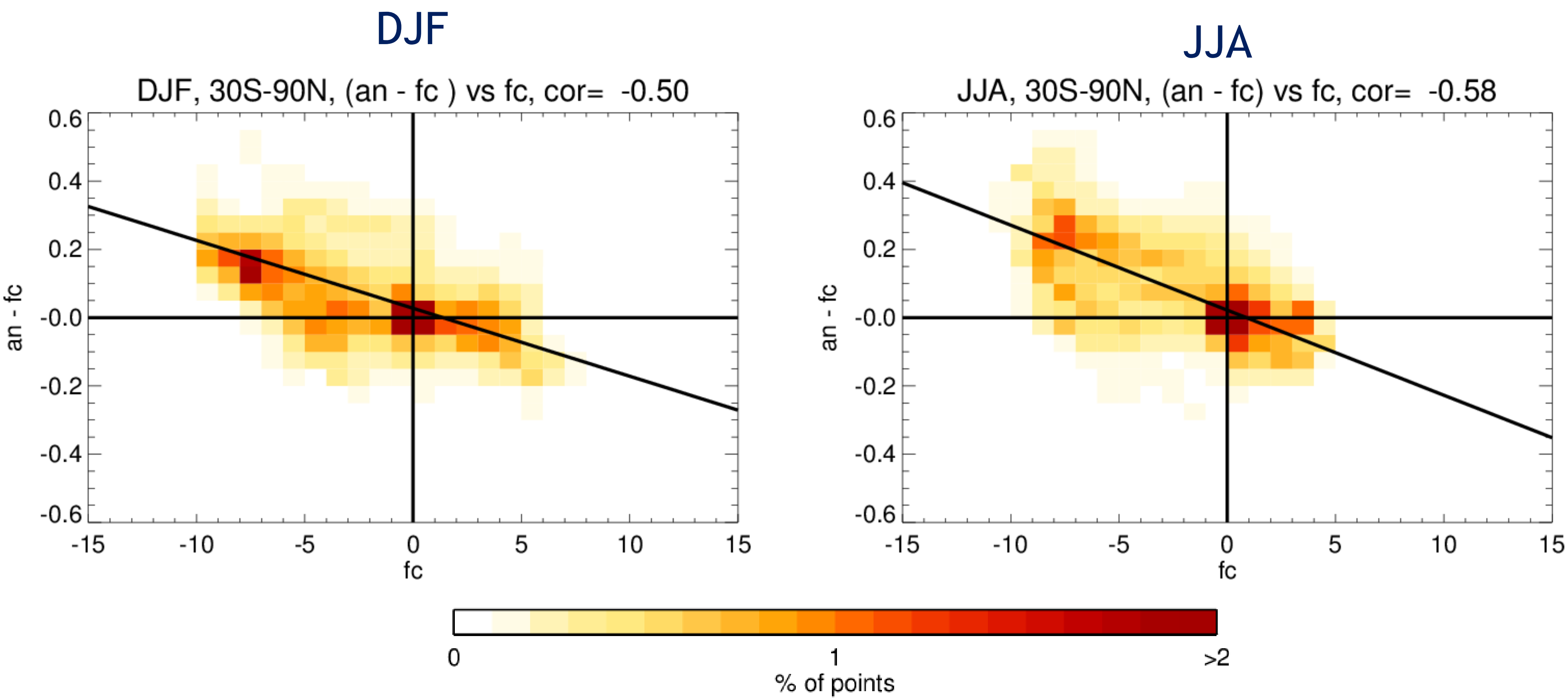
CMIP5 momentum budget as a function of season



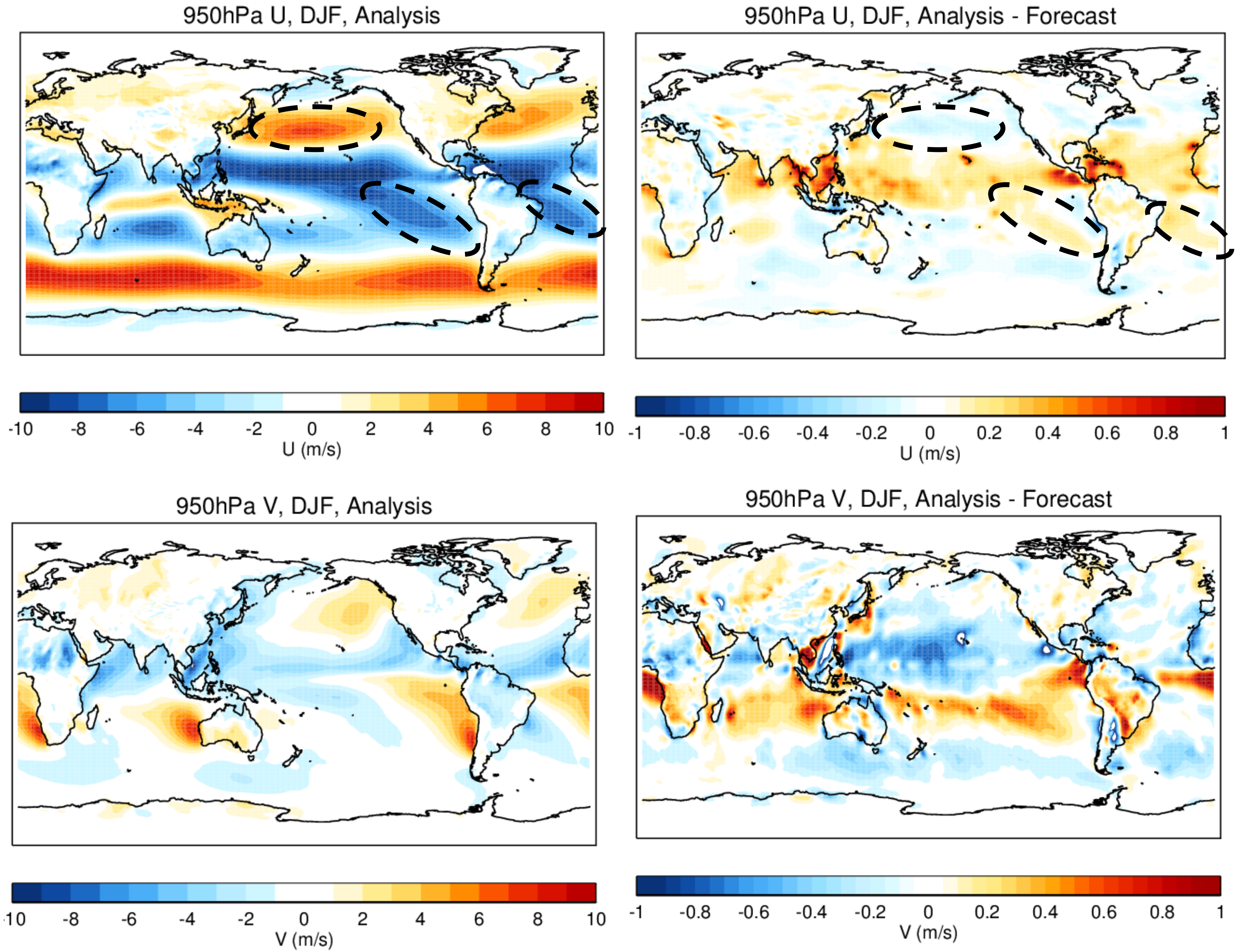
MERRA Budget

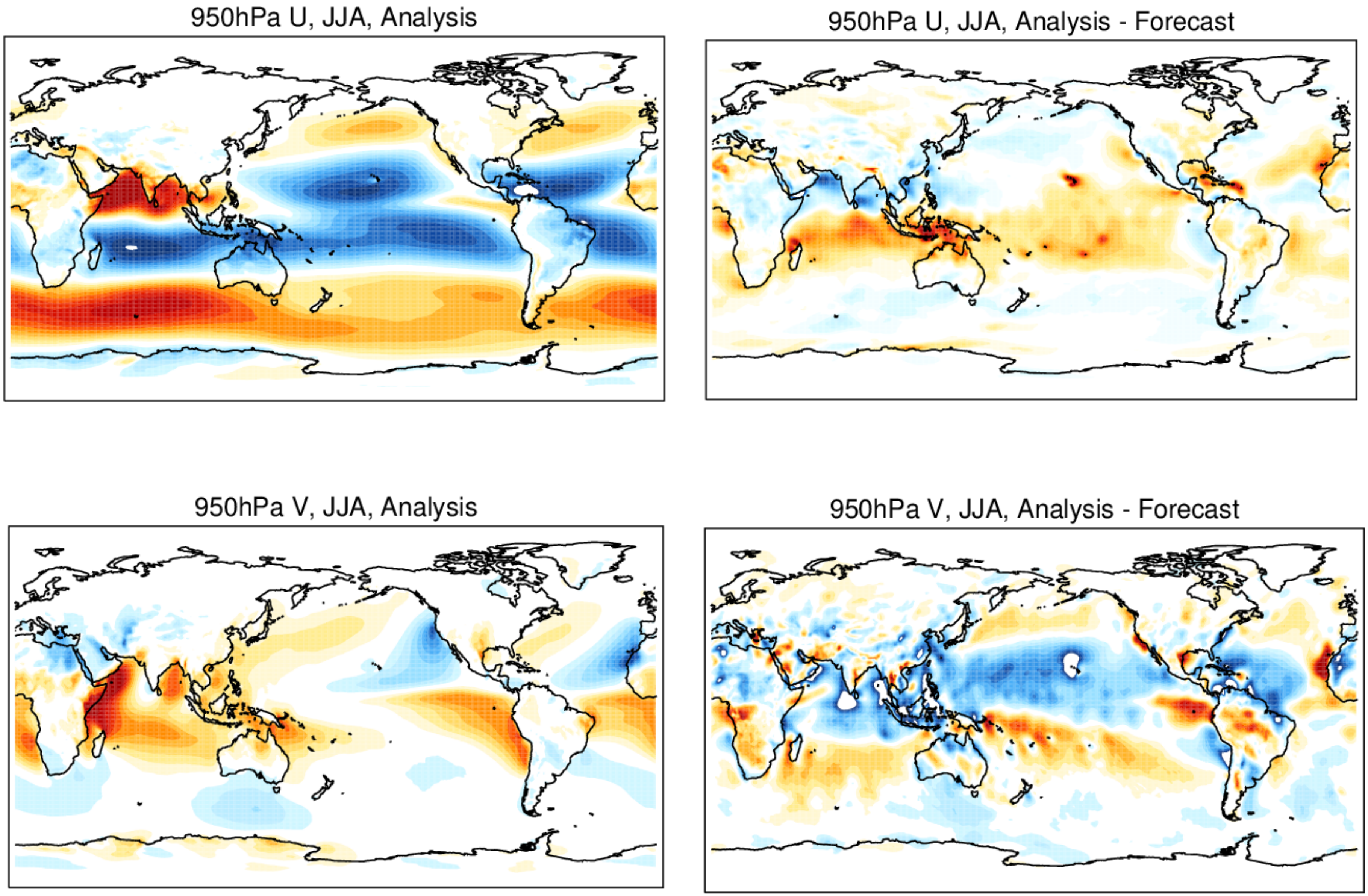


(Analysis – Forecast) vs Forecast
Ocean points north of 30S, 950hPa



Negative correlation → assimilation of observations acts to reduce the climatological low level winds.


950hPa U, DJF, Analysis
950hPa U, DJF, Analysis - Forecast
-10 -8 -6 -4 -2 0 2 4 6 8 10
U (m/s)
-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1
U (m/s)
950hPa V, DJF, Analysis
950hPa V, DJF, Analysis - Forecast
-10 -8 -6 -4 -2 0 2 4 6 8 10
V (m/s)
-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1
V (m/s)


950hPa U, JJA, Analysis
950hPa U, JJA, Analysis - Forecast
950hPa V, JJA, Analysis
950hPa V, JJA, Analysis - Forecast

Ocean Currents

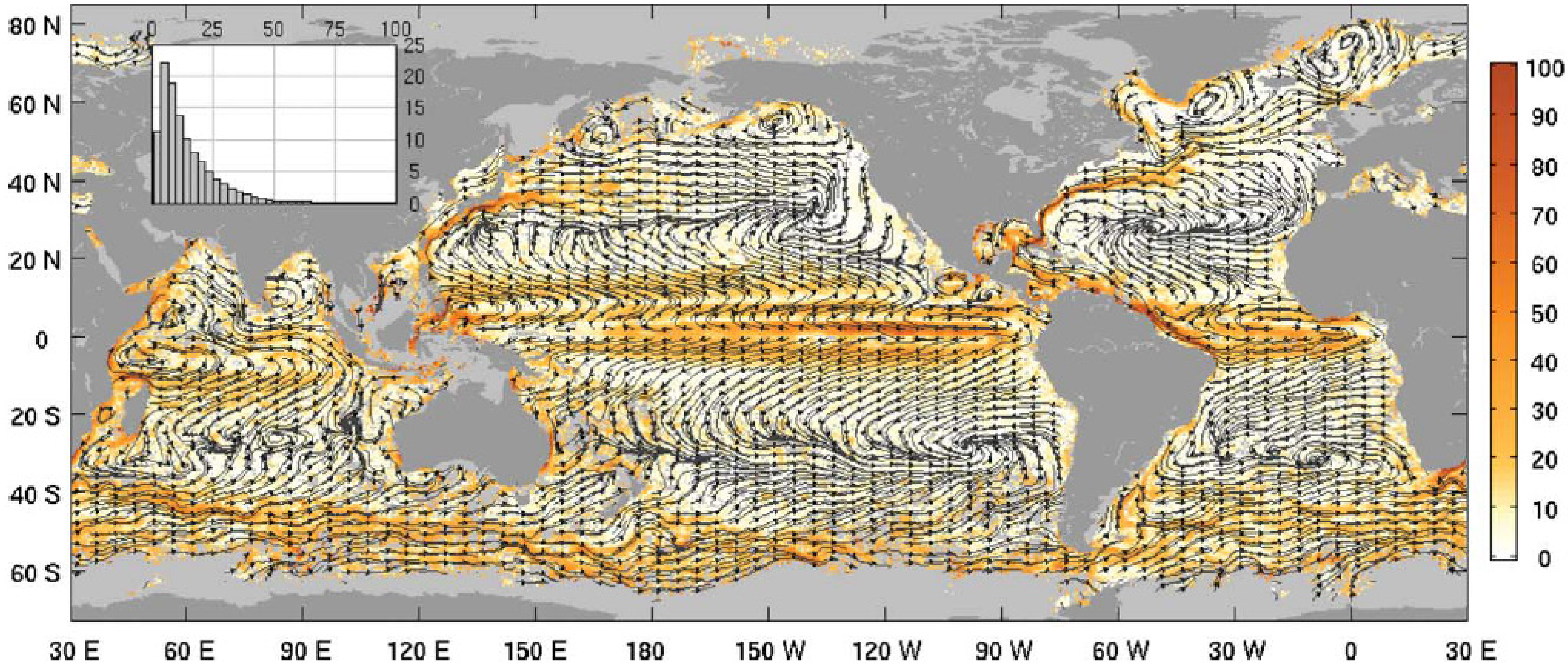
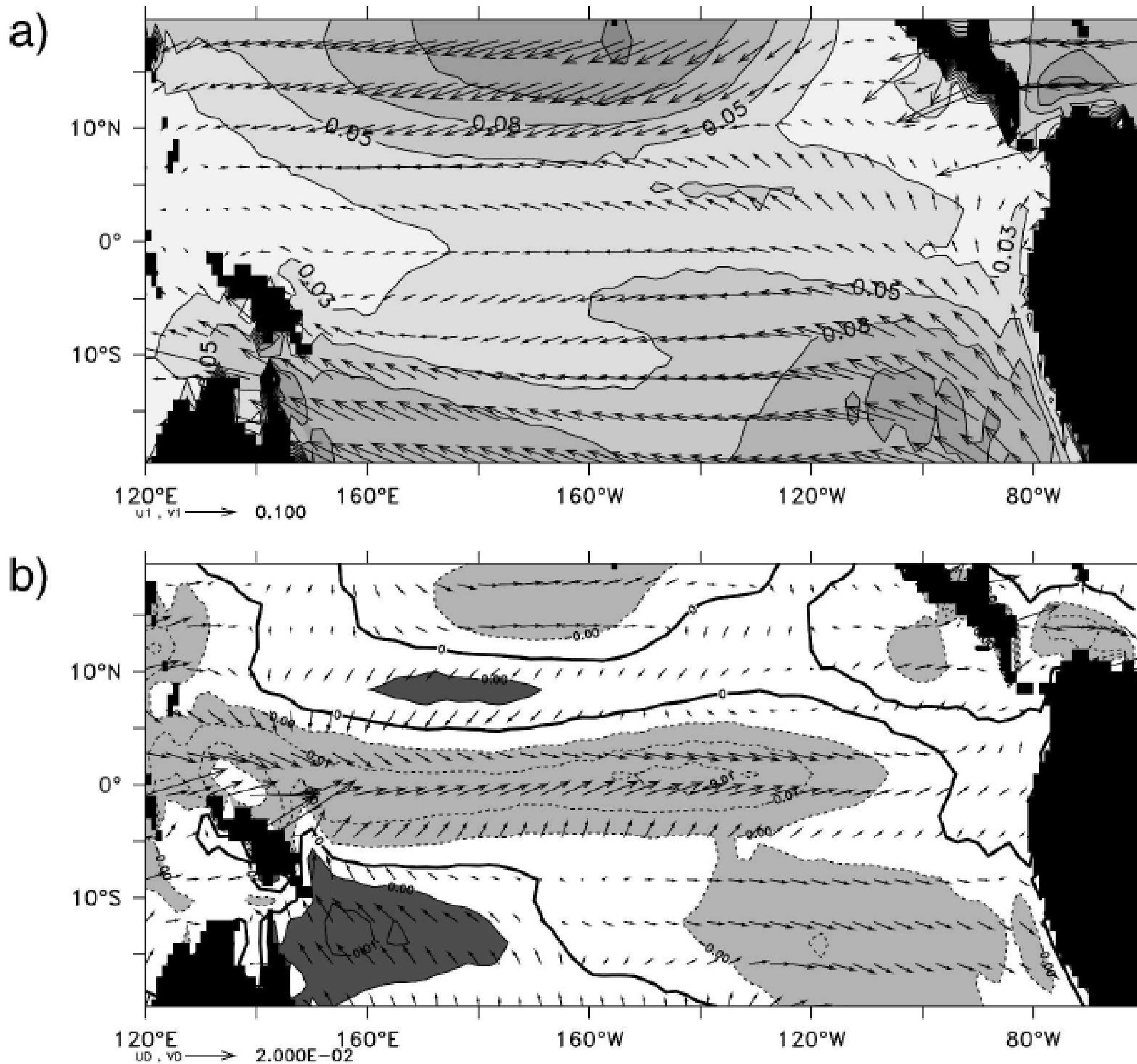


Figure 2. Mean current speeds (colors, in cm s^{-1}) from near-surface drifter data with streamlines (black lines). Streamlines are calculated from spatially smoothed currents to indicate flow direction and qualitatively illustrate large-scale circulation features, including surface divergence. Light gray areas have less than 10 drifter days per bin (0.8 per square degree). In addition, only bins with mean current speeds statistically different from zero at one standard error of the mean are shaded. Inset (top left) shows histogram of mean current speed (cm s^{-1}, horizontal axis, from 0 to 100 at 3.125 cm s^{-1} intervals) versus number of bins (in kilobins, vertical axis, from 0 to 25,000 bins).

Lumpkin and Johnson (2013)



Jungclaus et al (2006)

All of these wind stress estimates rely on some formulation of the drag coefficient

$$\tau = \rho C_D \vec{v}_{10} |\vec{v}_{10}|$$

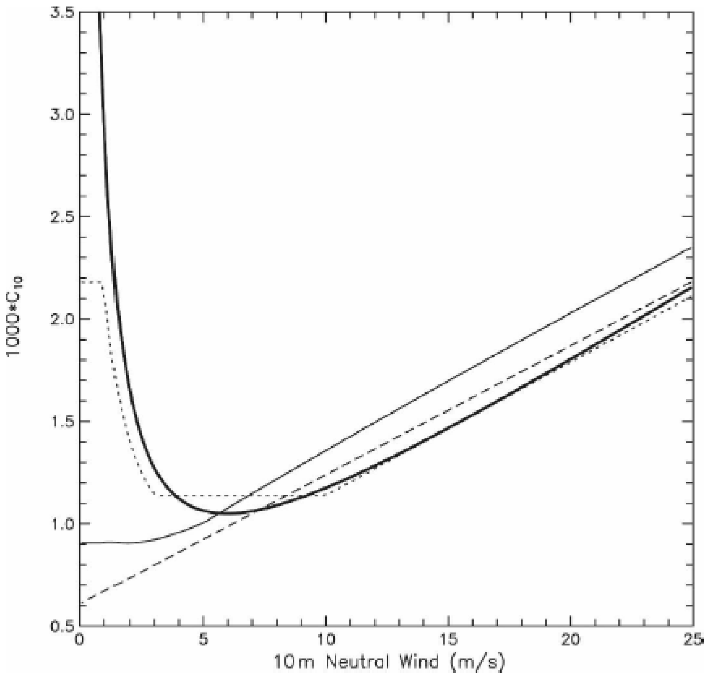
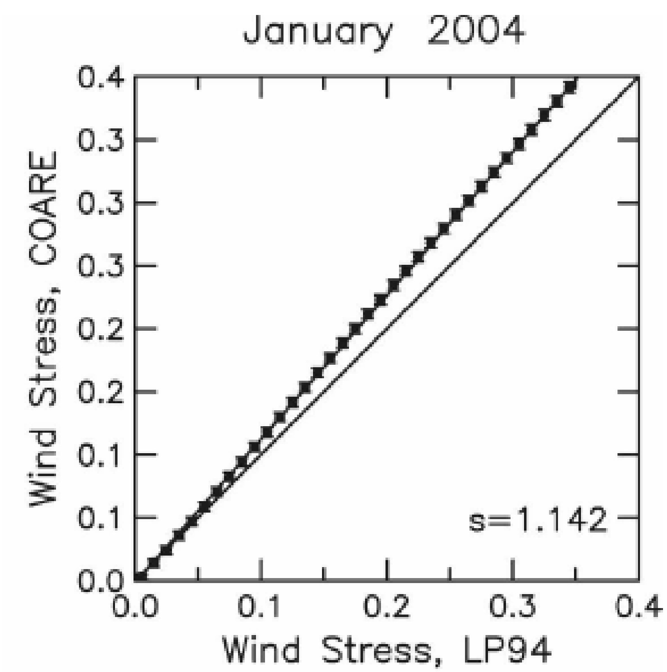
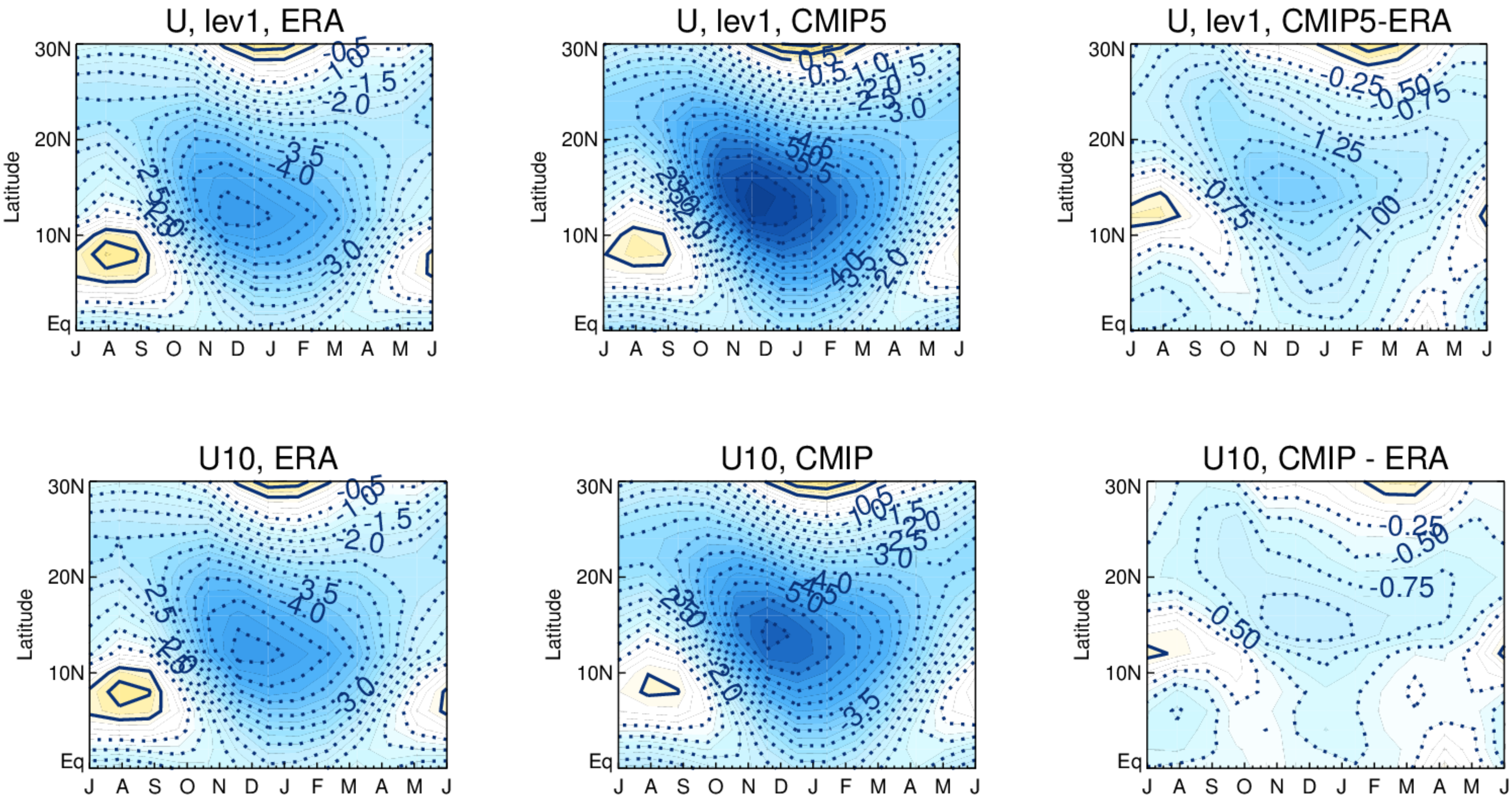


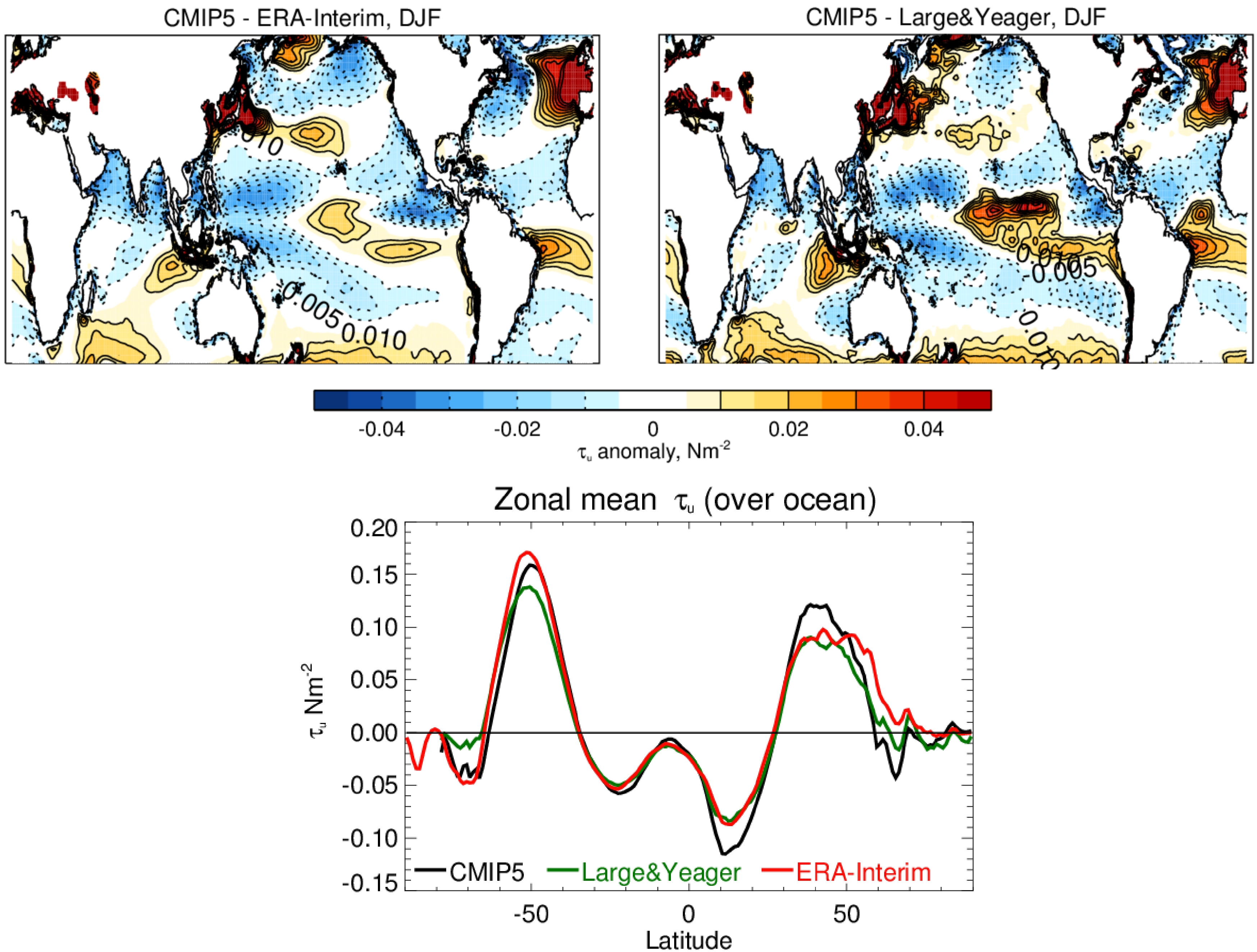
FIG. B1. The wind speed dependence of drag coefficients for neutrally stabile conditions: the 1994 modified Large and Pond formulation described in the appendix of Large et al. (1994) (thick solid line); the 1990 modified Large and Pond formulation described by Trenberth et al. (1990) (dotted line); the Smith (1980) formulation (dashed line); and the COARE 3.0 formulation presented by Fairall et al. (2003) (thin solid line).

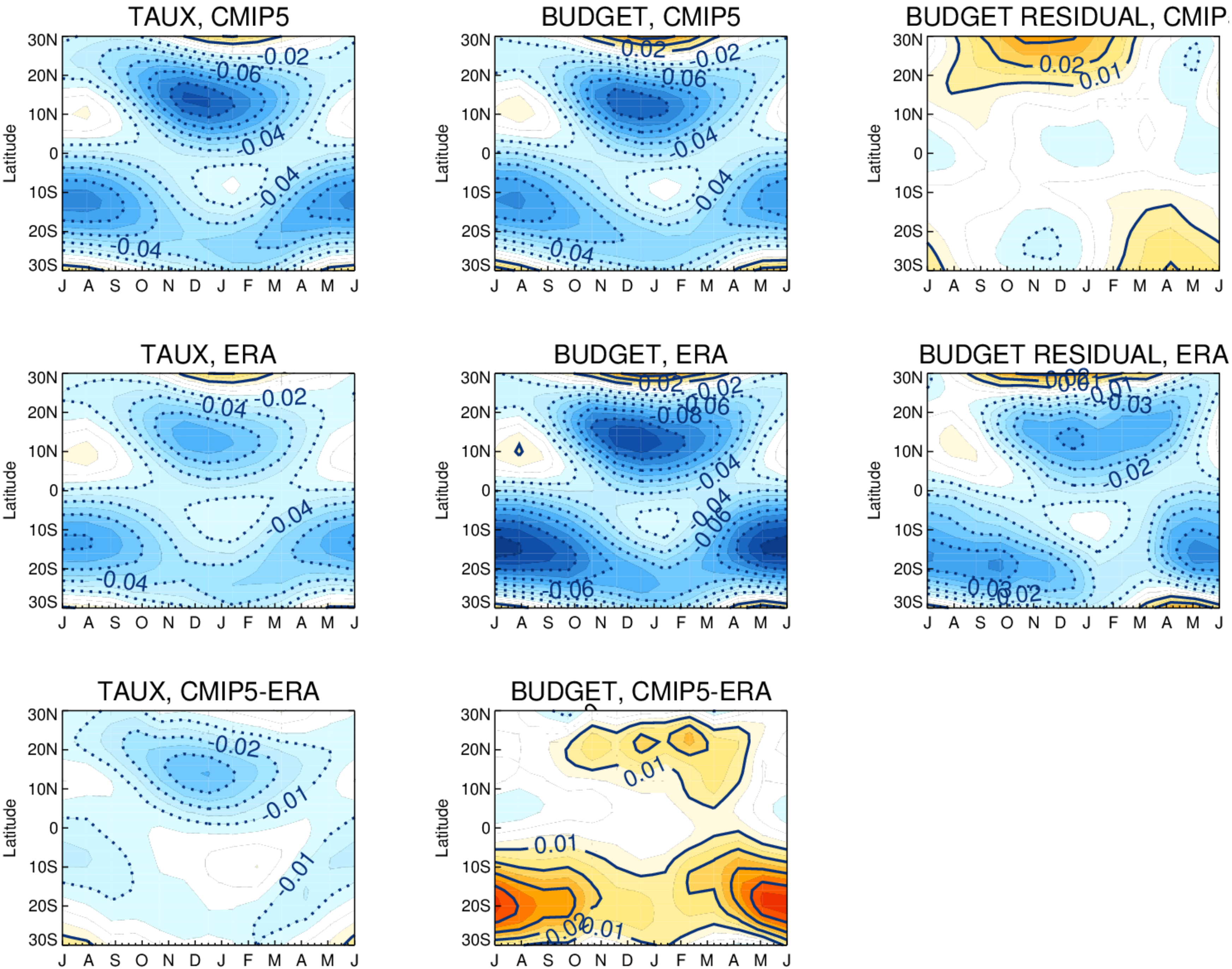


Risien and Chelton (2008)

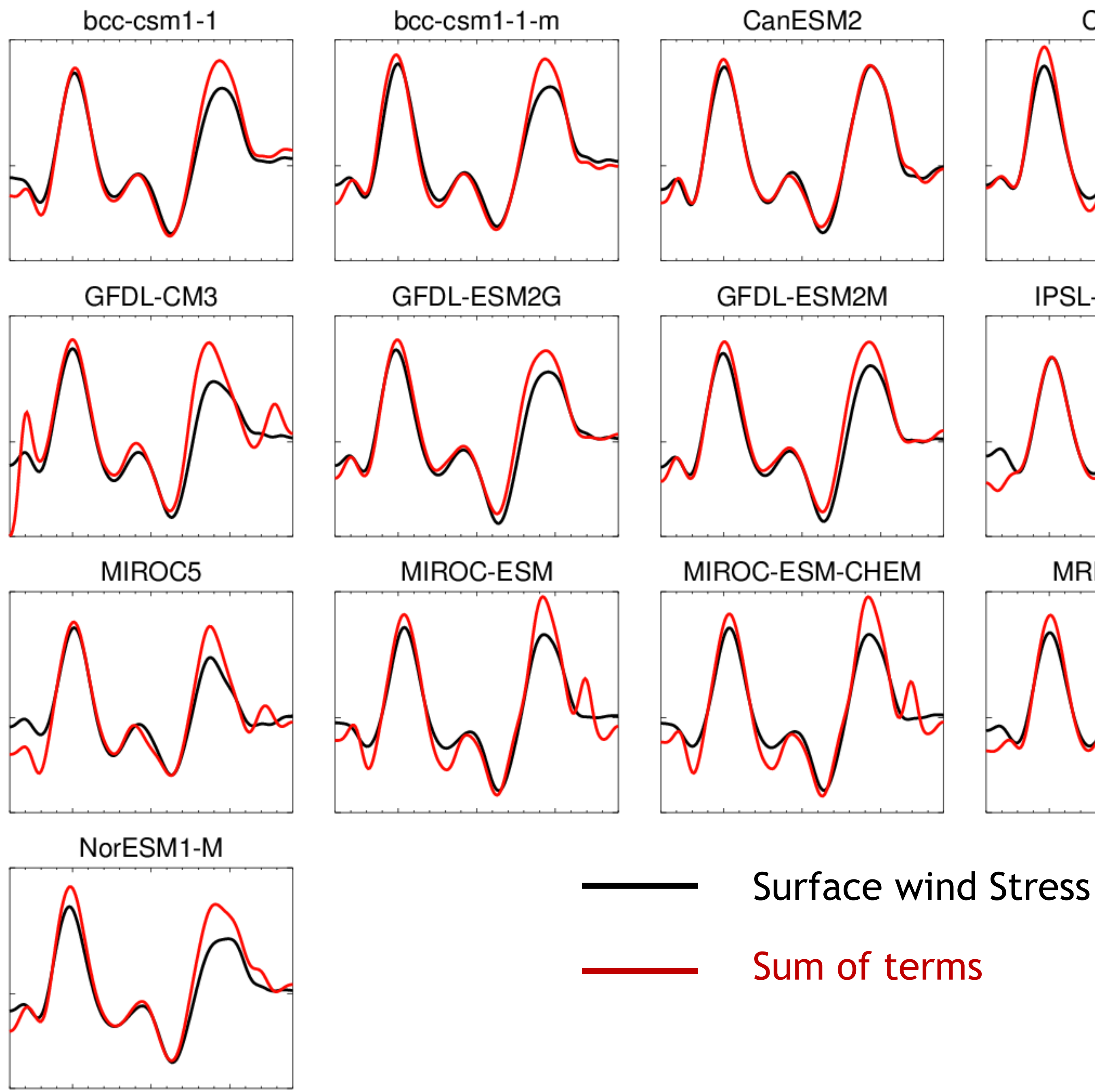


U, lev1, ERA
U, lev1, CMIP5
U, lev1, CMIP5-ERA
U10, ERA
U10, CMIP
U10, CMIP - ERA
Latitude
30N
20N
10N
Eq
J A S O N D J F M A M J

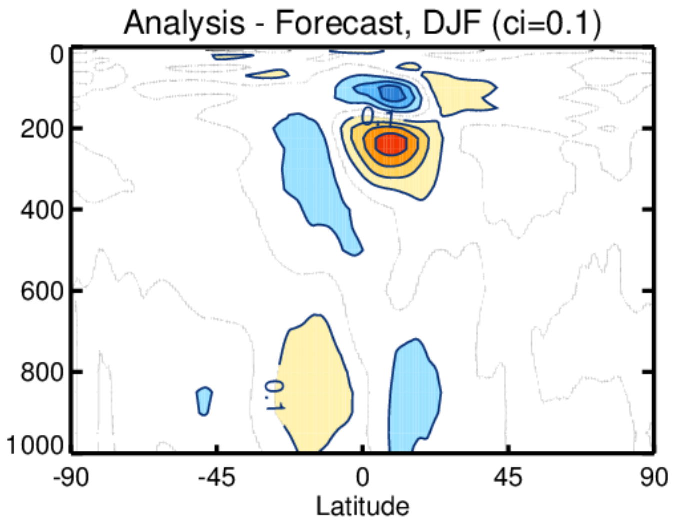

CMIP5 - ERA-Interim, DJF
CMIP5 - Large&Yeager, DJF
0.005
0.010
-0.005
-0.04
-0.02
0
0.02
0.04
τ_u anomaly, Nm^{-2}
Zonal mean τ_u (over ocean)
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
τ_u Nm^{-2}
-50
0
50
Latitude
CMIP5
Large&Yeager
ERA-Interim



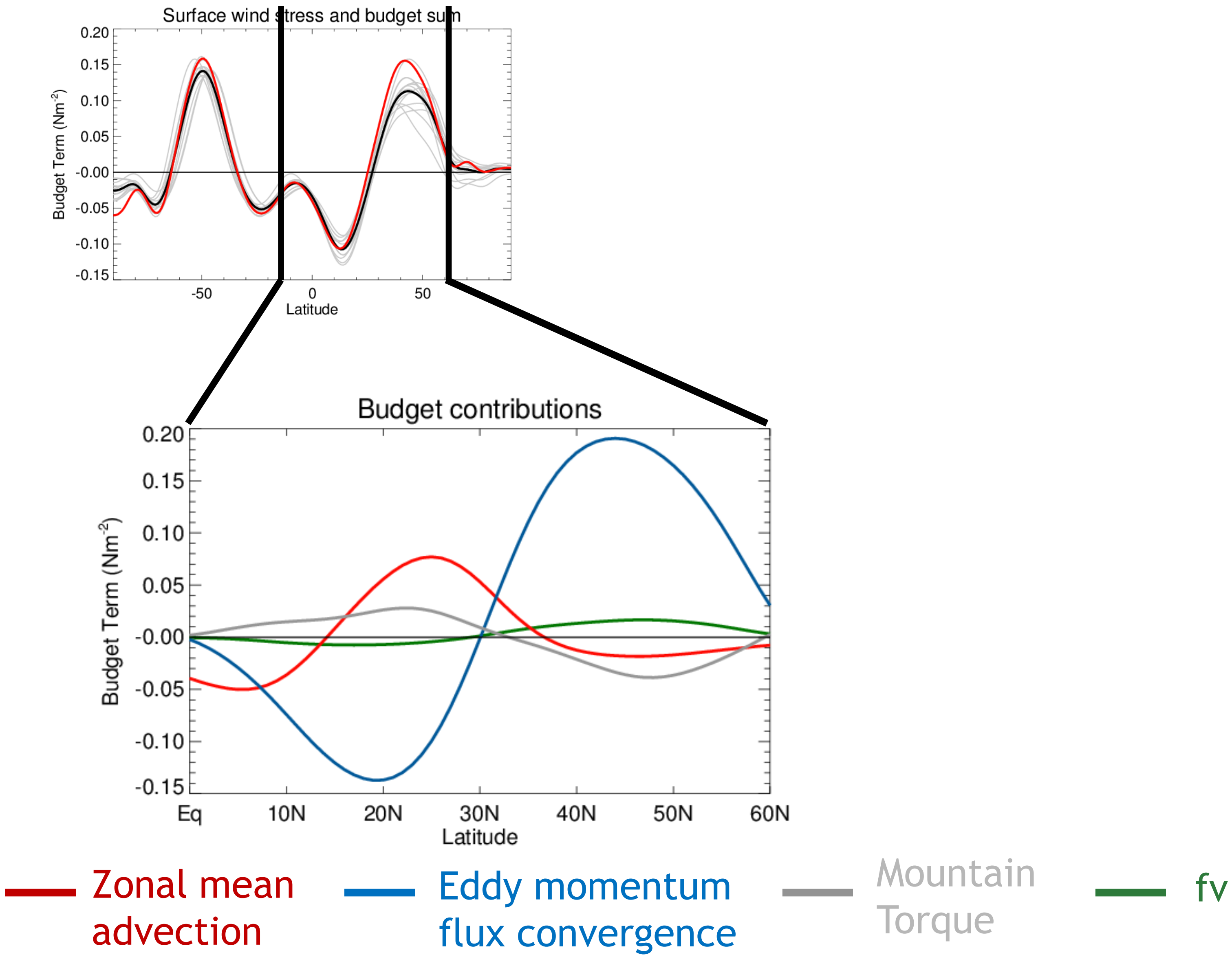
TAUX, CMIP5
BUDGET, CMIP5
BUDGET RESIDUAL, CMIP
TAUX, ERA
BUDGET, ERA
BUDGET RESIDUAL, ERA
TAUX, CMIP5-ERA
BUDGET, CMIP5-ERA
Latitude
30N
20N
10N
0
10S
20S
30S
J A S O N D J F M A M J
-0.02
-0.04
-0.06
-0.08
0.02
0.01
-0.01
-0.03


bcc-csm1-1
bcc-csm1-1-m
CanESM2
CCSM4
GFDL-CM3
GFDL-ESM2G
GFDL-ESM2M
IPSL-CM5A-MR
MIROC5
MIROC-ESM
MIROC-ESM-CHEM
MRI-CGCM3
NorESM1-M
Surface wind Stress
Sum of terms

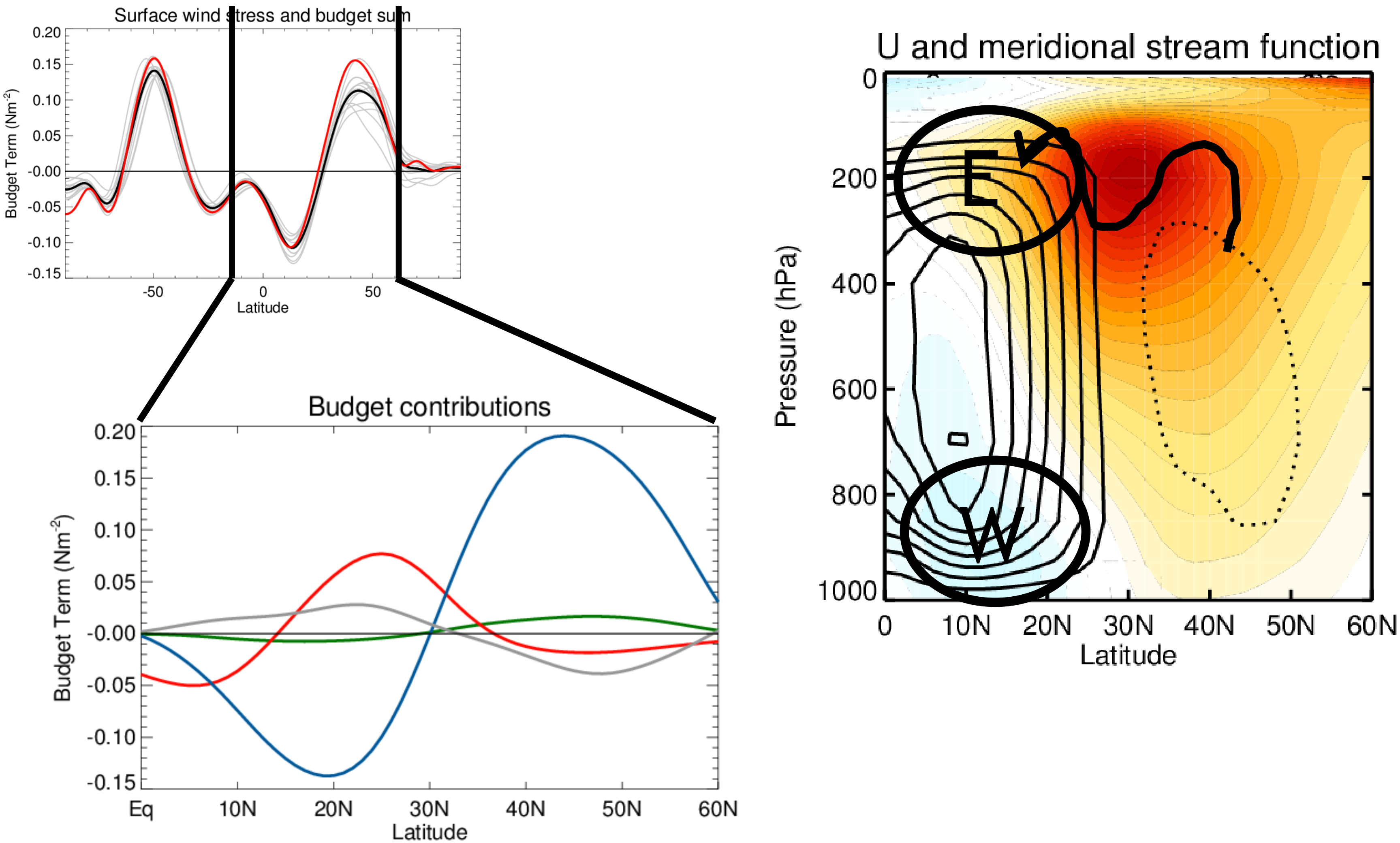
Seasonality of v Analysis – Forecast differences



Contributors to the budget in the CMIP5 models



Contributors to the budget in the CMIP5 models

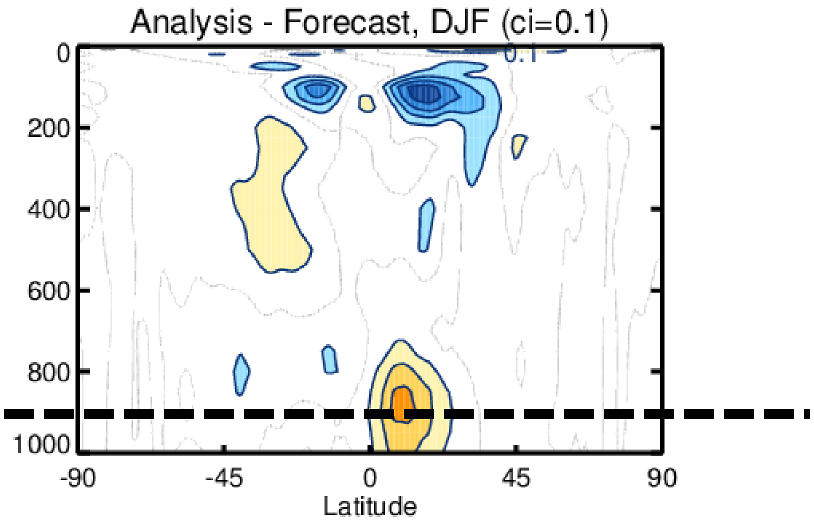


Zonal mean advection

Eddy momentum flux convergence

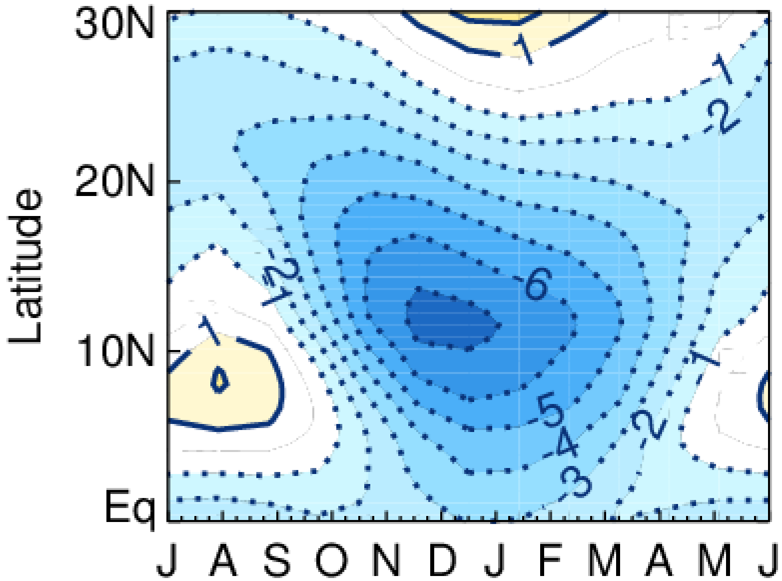
Mountain Torque

fv

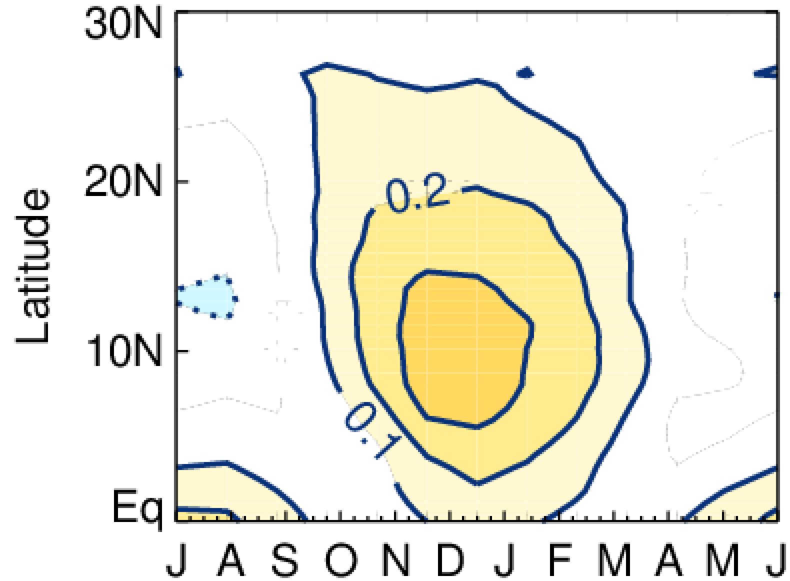


900hPa zonal mean zonal wind

ANALYSIS



ANALYSIS - FORECAST



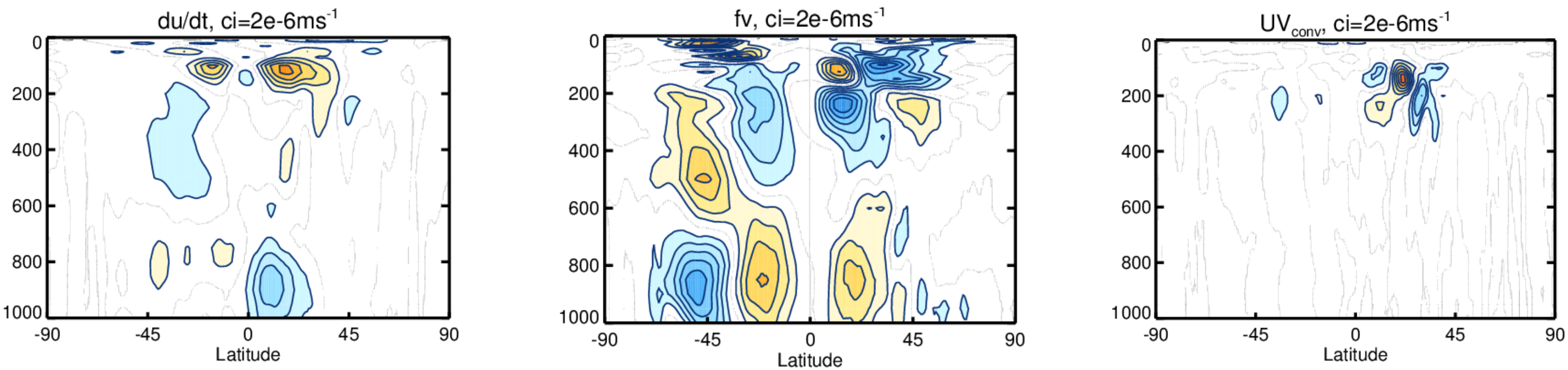
$$\frac{\partial u}{\partial t} = fv + UV_{conv} + Z$$

E W W ← Expect

$$\underbrace{\frac{\partial u}{\partial t} - fv - UV_{conv}}_{E} = Z$$

Forecast Evolution compared to Analysis Evolution = (Forecast – Analysis)

$\frac{\partial u}{\partial t}$ fv UV_{conv}



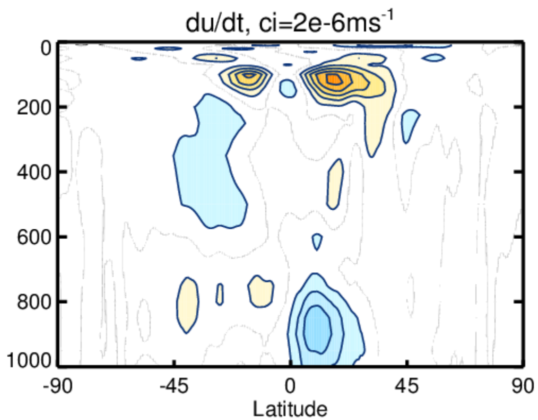
$$\underset{E\uparrow}{\frac{\partial u}{\partial t}} = \underset{W\uparrow}{fv} + \underset{W\uparrow}{UV_{conv}} + M + F_u + Z$$

← Expect →

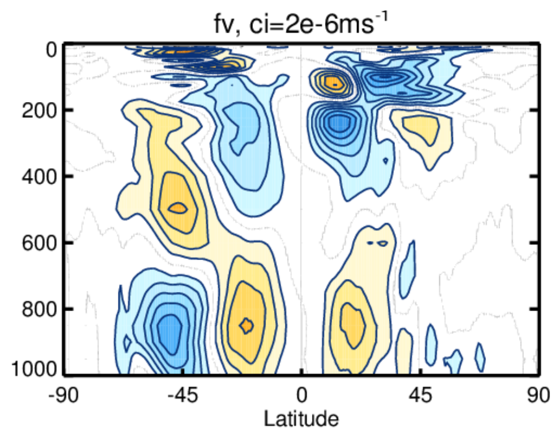
$$\underbrace{\frac{\partial u}{\partial t} - fv - UV_{conv} - M}_{E\uparrow} = F_u + Z$$

Forecast Evolution compared to Analysis Evolution = (Forecast – Analysis)

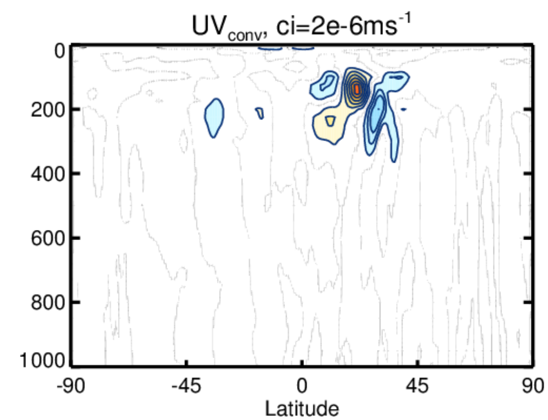
$$\frac{\partial u}{\partial t}$$



$$fv$$



$$UV_{conv}$$



$$\frac{\partial u}{\partial t} = fv + UV_{conv} + M + F_u + Z$$

E W W

←Expect→

$$\underbrace{\frac{\partial u}{\partial t} - fv - UV_{conv} - M}_{E} = F_u + Z$$

Forecast Evolution compared to Analysis Evolution = (Forecast – Analysis)

$$\frac{\partial u}{\partial t} - fv - UV_{conv}$$