Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

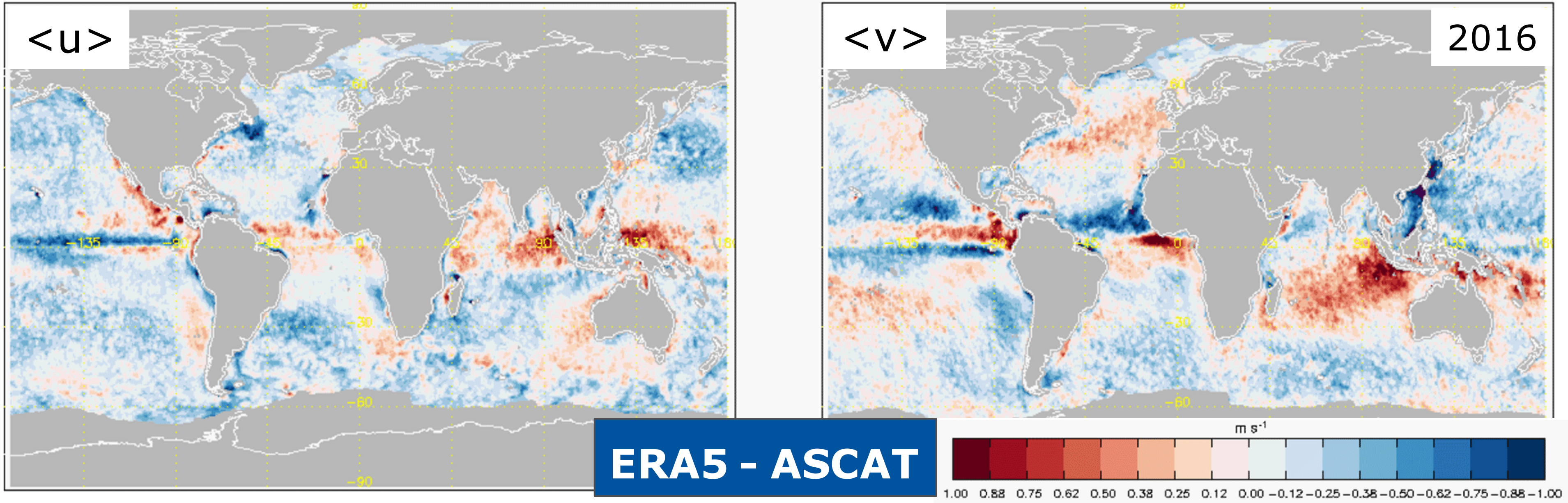
BLUE for the Scatterometer Constellation

Ad Stoffelen

Maria Belmonte, Ana Trindade, Marcos Portabella,
Giovanna De Chiara

Zonal, Meridional Errors

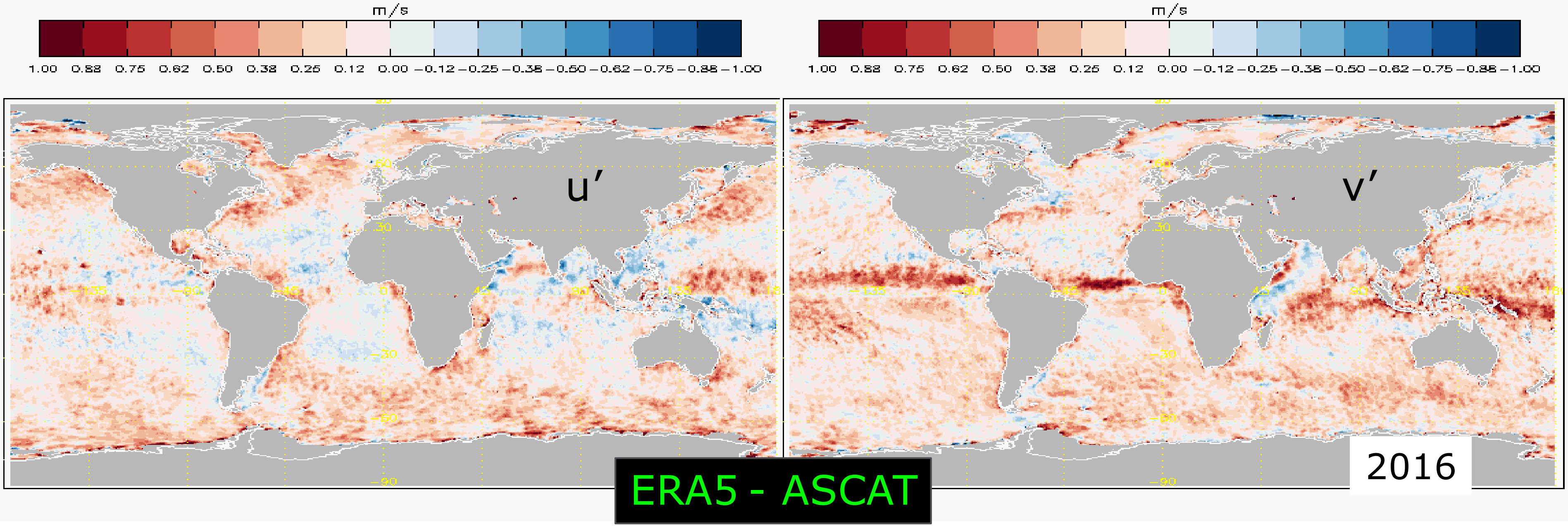
- ERA5 has substantial spatial bias patterns on large scales and small scales
- After GlobCurrent correction



→ Excess mean <u>model</u> zonal winds (blues at mid-latitudes and subtropics)
→ Defective mean <u>model</u> meridional winds (reds at mid-lats and tropics)

Belmonte & Stoffelen, 2019

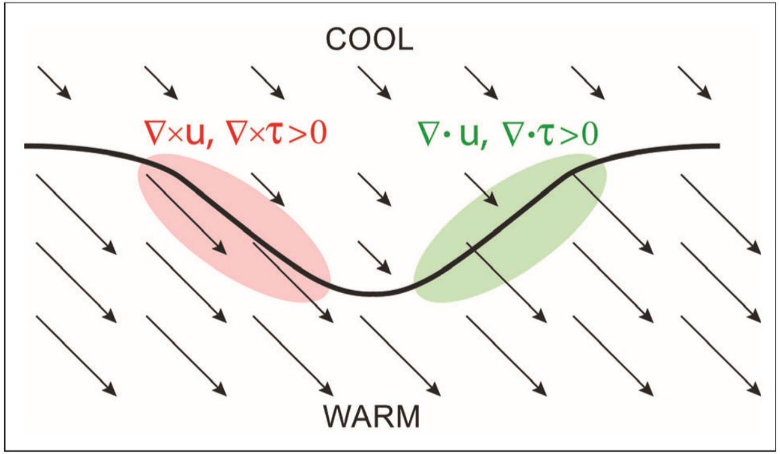
Transient Wind Errors



Belmonte & Stoffelen, 2019

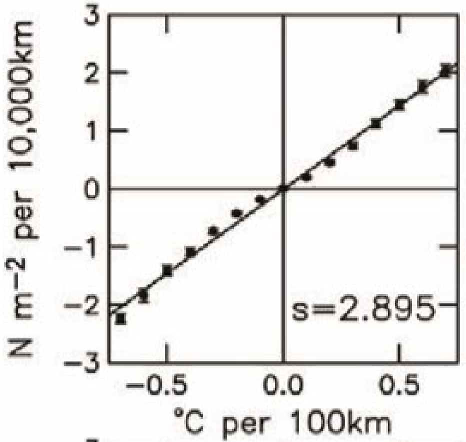
→ Defective local model wind variability overall:
  - Zonal (left) and meridional (right) at mid-to-high latitudes
  - Particularly meridional deficit along ITCZ
  - Locally enhanced along WBCs (ARC, ACC, GS, KE currents)

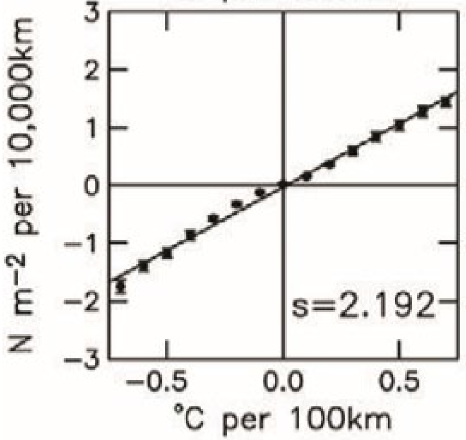
Errors in Ocean Forcing



$\sim 0.5\ \mathrm{K} / 100\ \mathrm{km}$
$\equiv 10^{-2}\ \mathrm{Nm}^{-2} / 100\ \mathrm{km}$
$\equiv 3\ \mathrm{ms}^{-1} / 100\ \mathrm{km}$

- Both wind and SST changes are easy to measure from space



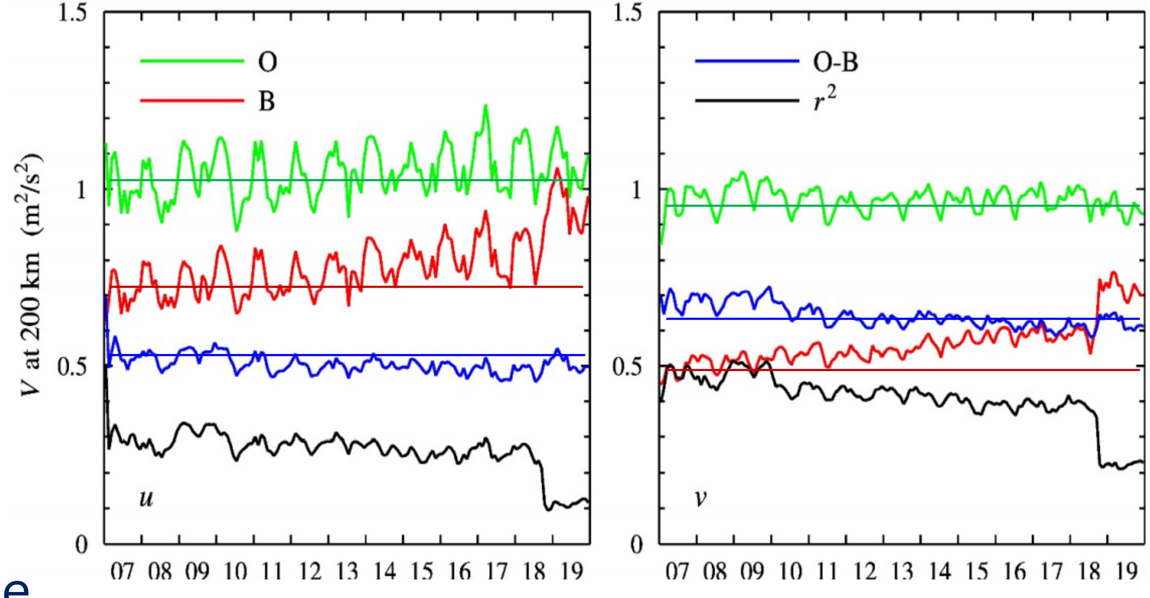


- Small ocean scales imply small wind scales
- Global NWP coupling is an order of magnitude weaker
- Effective horizontal global NWP resolution is about 150 km
- SST gradients are associated with ocean currents and these are not measured on these scales

Chelton et al, 2004; 2010

ECMWF OPS imProves

- Variances on scales < 200 km only
- Scatterometer O variance under 200 km constant
- Variance B increases to 90% (u), 70% (v) of O
- O-B is constant

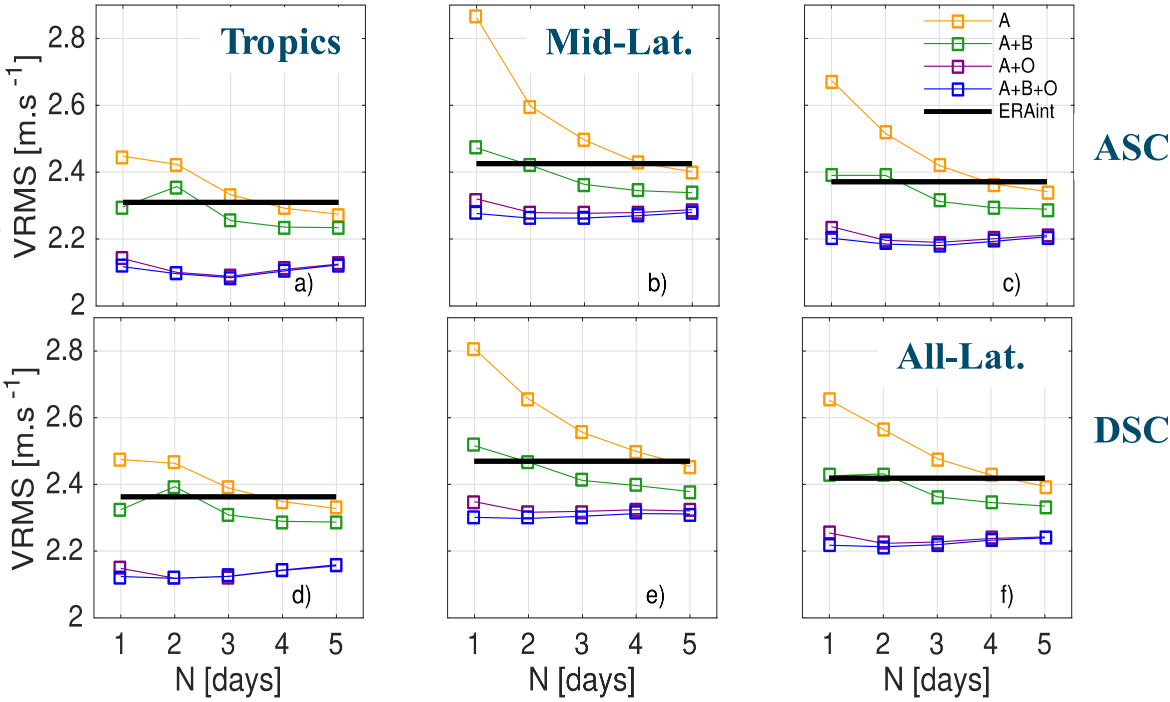


- ➢ Better grids or coupling (2018) do not revolutionize model skill, though B variance increase in 2018 is encouraging
- ➢ Rather slow progress in need for more observations, e.g., constellation
- ➢ How to better exploit the constellation data, following BLUE ?

Stoffelen et al., 2020

Scatterometer biases

- 9:30: ASCAT-A (A) & -B (B)
- 12:00: OceanSat-2 (O)
- Compute local bias O-B
- Average O-B over N days (SC)
- Takes away weather errors
- Add SC to ERA fields: ERA*
- Verify ERA* with the HY2A scatterometer winds at 6:00
- 20% of variance reduction in O-B VRMS is substantial!
- Apply in data assimilation
- E.g., local VARBC



Trindade et al., 2020

Conclusions

- NWP fields show rather large systematic local biases in both the partitioning into mean and transient, zonal and meridional winds, i.e., on large and small scales
- The ocean current correction contributes notably: it relieves the zonal mean wind biases globally, but enhances differences connected with SST gradient effects over the equatorial cold tongues and WBC jets and deteriorates meridional variability errors
- ➢ The remaining large (10%) systematic and random errors should be accounted for to benefit atmospheric surface wind data assimilation, following BLUE
- ➢ ERA* also improves fluxes and the forcing of ocean models
- ➢ The ERA* method needs to be tested in applications (ongoing)
- ➢ The empirical ERA* corrections need to be linked to errors in processes, i.e., dynamics, PBL, moist convection, air-sea interaction dynamics and processes

Stoffelen and Vogelzang, 2021

Work in Progress

Short-term

- Apply the method to the ECMWF ERA5 and OPS dataset > ERA5*, resp. OPS*
- Test ERA*/OPS* wind fields in global/regional ocean (coupled) models
- Apply other optimizations, e.g., supermodding, cf. Mile et al., 2021, 4D-var

Long-term

- Work towards ERA* near-real time and multi-year L4 wind products (CMEMS)
- Correct local biases in ECMWF data assimilation (VARBC) for better initialization
- Attribute wind biases and variances to model errors, both in dynamical closure and parameterizations (fluxes, convection, PBL, …)
- Test atmosphere-ocean coupling stresses with scatterometers

The following slides explain method, results and conclusions of the foregoing slides

Errors in Ocean Winds

- ERA5 10m stress-equivalent winds (w.r.t. earth frame)
- CMEMS ASCAT Level-3 REP observed ocean-current-relative wind data
- Wind-related drifts are part of scatterometer (and ERA) winds
- Trial with ocean current correction (GlobCurrent) of ERA to make it ocean-relative
- Differences:
  - Zonal and meridional mean wind
  - Zonal and meridional transient wind
  - Wind stress curl
  - Wind divergence
- Differences mainly reveal ERA errors since ASCAT biases and errors are small as verified with buoy, model and scatterometer comparisons

Belmonte & Stoffelen, 2019

Model Wind Errors

Underestimation of wind turning in NWP model: surface winds more aligned to geostrophic balance above than to pressure gradient below → stable model winds are more zonal with reduced meridional flows

Sandu (ECMWF) reports that turbulent diffusion is too large (enlarged to reduce sub-grid mesoscale variability) which helps improve the representation of synoptic cyclone development at the expense of reducing the ageostrophic wind turning angle ...

→ It is a problem that the ocean is forced in the wrong direction though

Other processes poorly represented include 3D turbulence on scales below 500 km (closure) and wide-spread wind downbursts in (tropical) moist convection

→ Atmospheric mesoscale variability stirs the ocean and enhances fluxes

Belmonte & Stoffelen, 2019

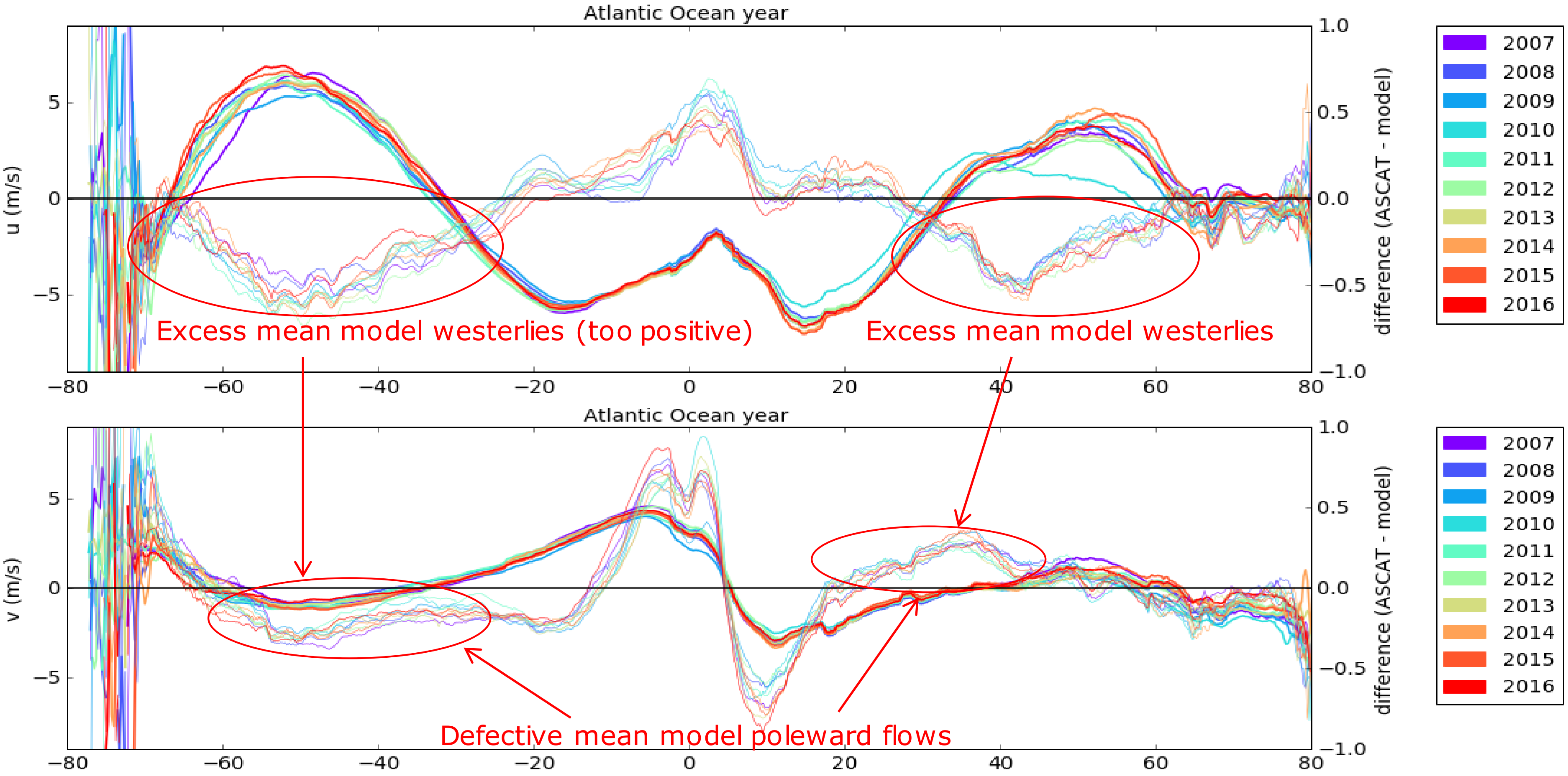
Missing mesoscale variability in reanalyses

Surface wind stress and the associated heat and momentum fluxes play an important role in driving surface and deep ocean circulation

The inability of reanalyses to reproduce mesoscale variability implies underestimation of atmospheric forcing at the air-sea boundary, with detrimental consequences for ocean forcing [Condron, “polar mesocyclones”, JGR, 2008] [Laffineur et al, “polar lows ERA interim”, MWR, 2014]

Belmonte & Stoffelen, 2019

Zonal and meridional errors

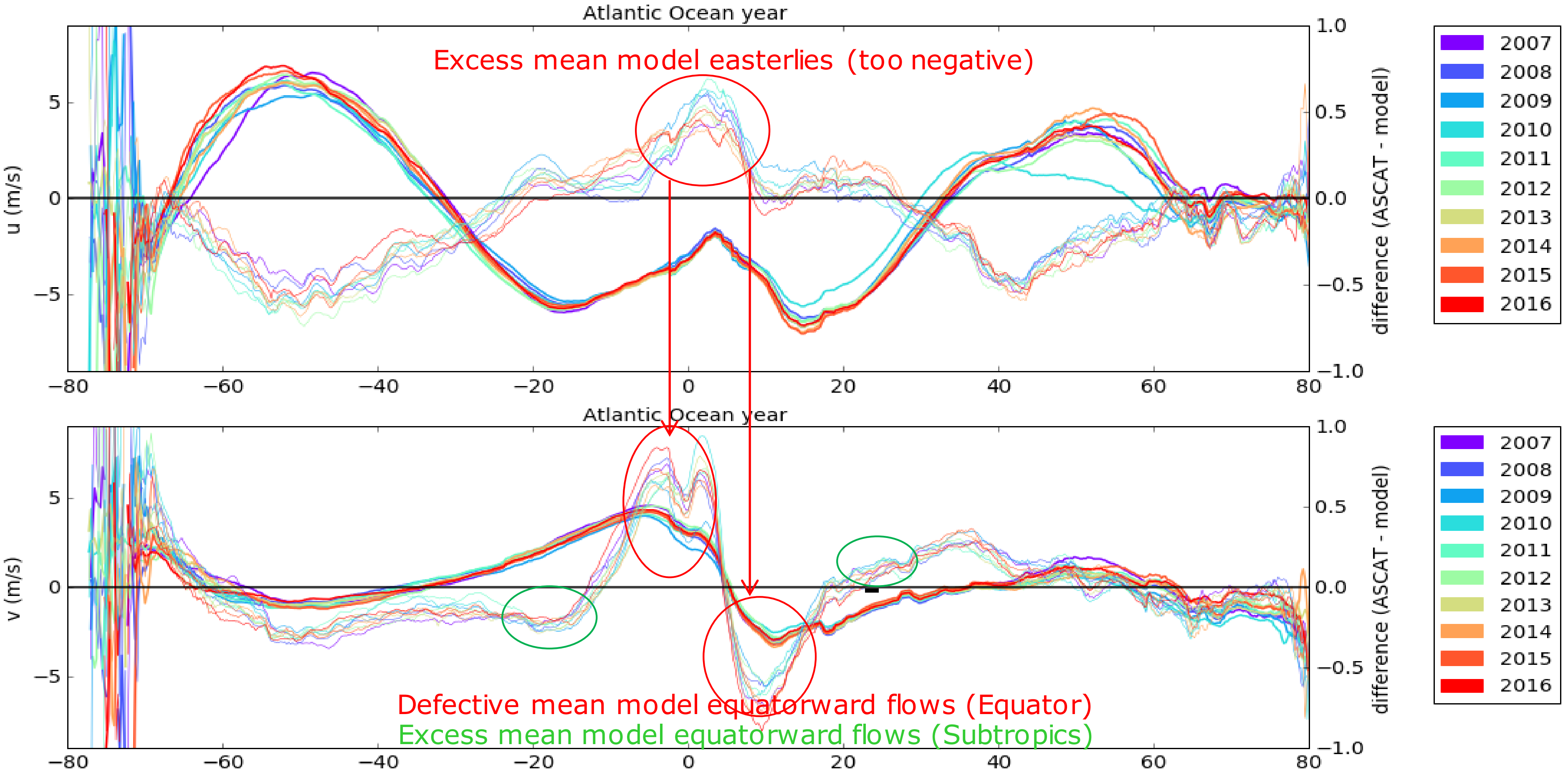


Excess mean model westerlies (too positive)

Excess mean model westerlies

Defective mean model poleward flows

Zonal and meridional errors

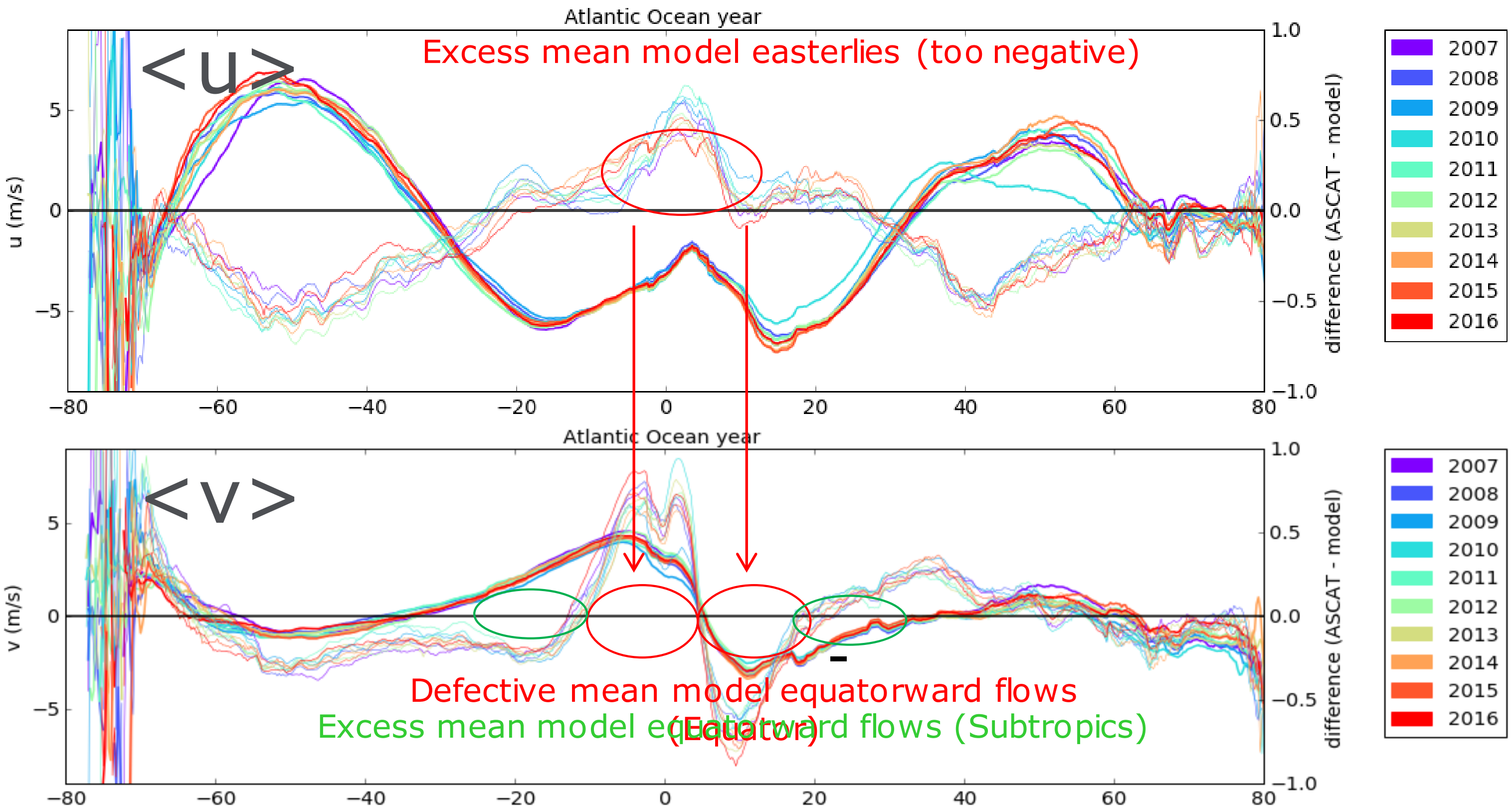


Excess mean model easterlies (too negative)

Defective mean model equatorward flows (Equator)

Excess mean model equatorward flows (Subtropics)

Zonal and meridional errors



Excess mean model easterlies (too negative)

Defective mean model equatorward flows (Equator)

Excess mean model equatorward flows (Subtropics)

ITCZ convergence??

Mean and eddy kinetic energies

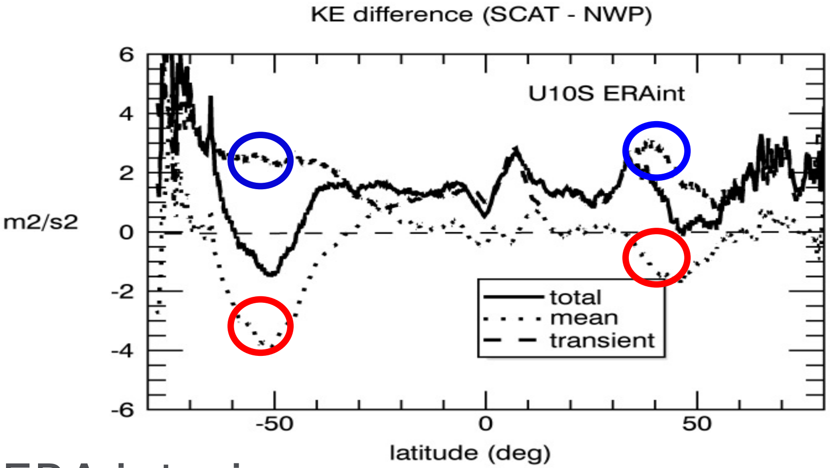
$u = \langle u \rangle + u'$

$v = \langle v \rangle + v'$

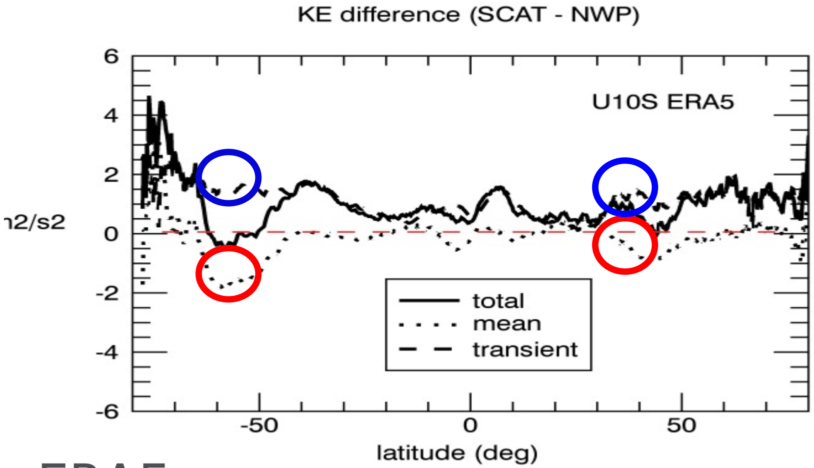
Average < > is over time (annual)

$$\mathrm{TKE} = \mathrm{MKE} + \mathrm{EKE}$$

$\langle u^2+v^2 \rangle$ $\langle u \rangle^2+\langle v \rangle^2$ $\langle u'^2 \rangle+\langle v'^2 \rangle$



ERA interim

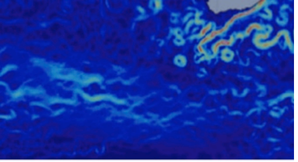


ERA5

→ ERA-int puts excess energy into mean flows and too little into eddies

→ In ERA5, mean flows have slowed down and eddy activity has increased

Belmonte & Stoffelen, 2019



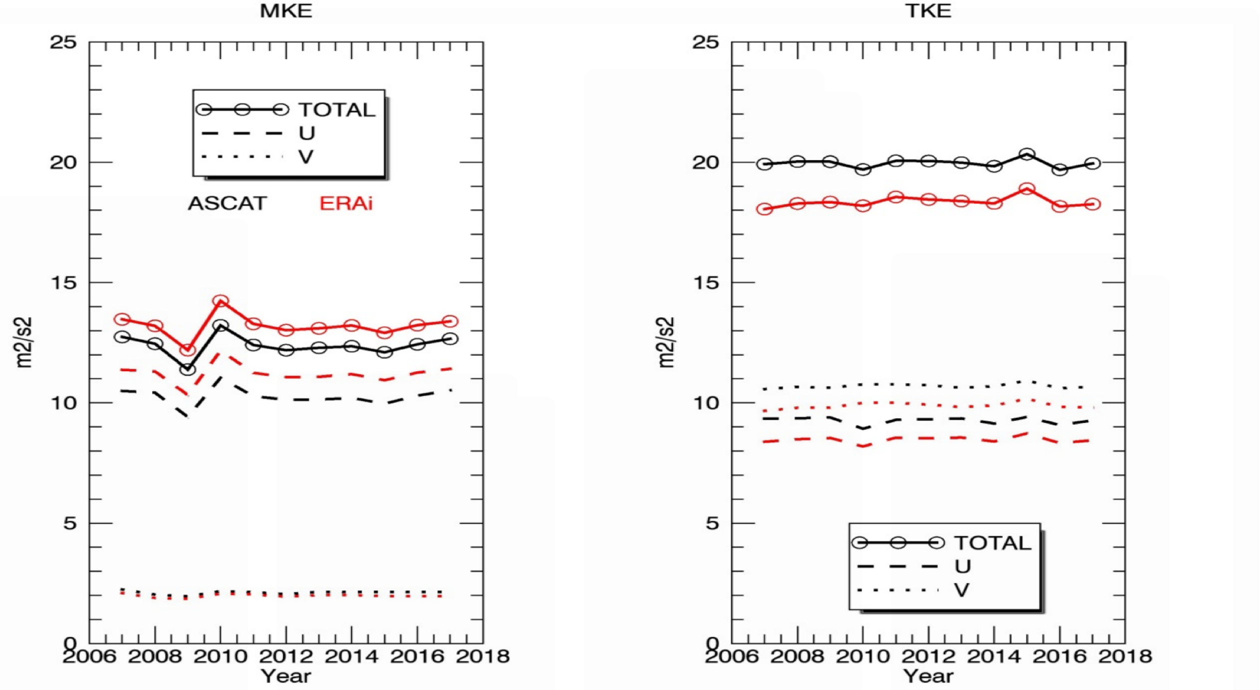
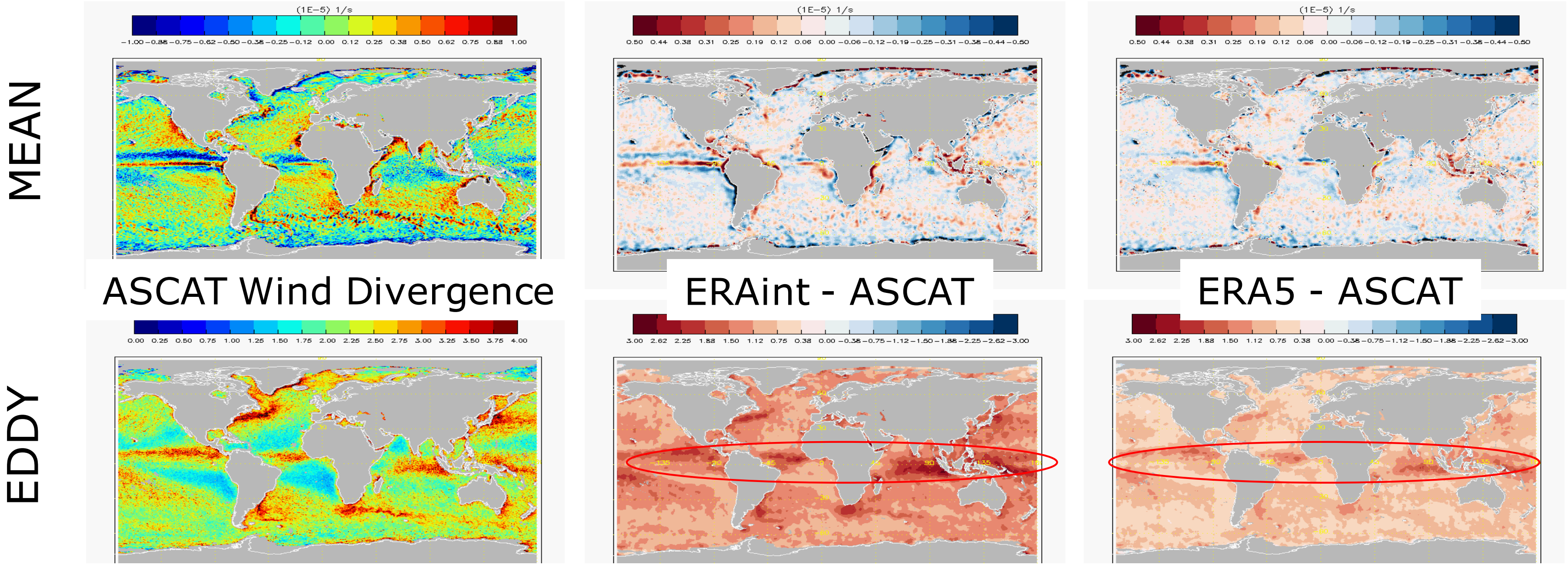


Figure 2.1.2: Time-series of globally averaged annual **mean kinetic energy** (MKE, left plot) and **turbulent kinetic energy** (TKE, right plot) contributions for the 2007-2017 period split into zonal and meridional components. The kinetic energy partition is shown for ASCAT observations (black) and ERA interim collocations (in red).

- On a global level, the ERA-int winds show that:
  - MKE is too high in the zonal, but low in the meridional
  - EKE is missing both in the zonal and meridional components

Belmonte & Stoffelen, 2019

Wind Divergence Errors



ASCAT Wind Divergence

ERAint - ASCAT

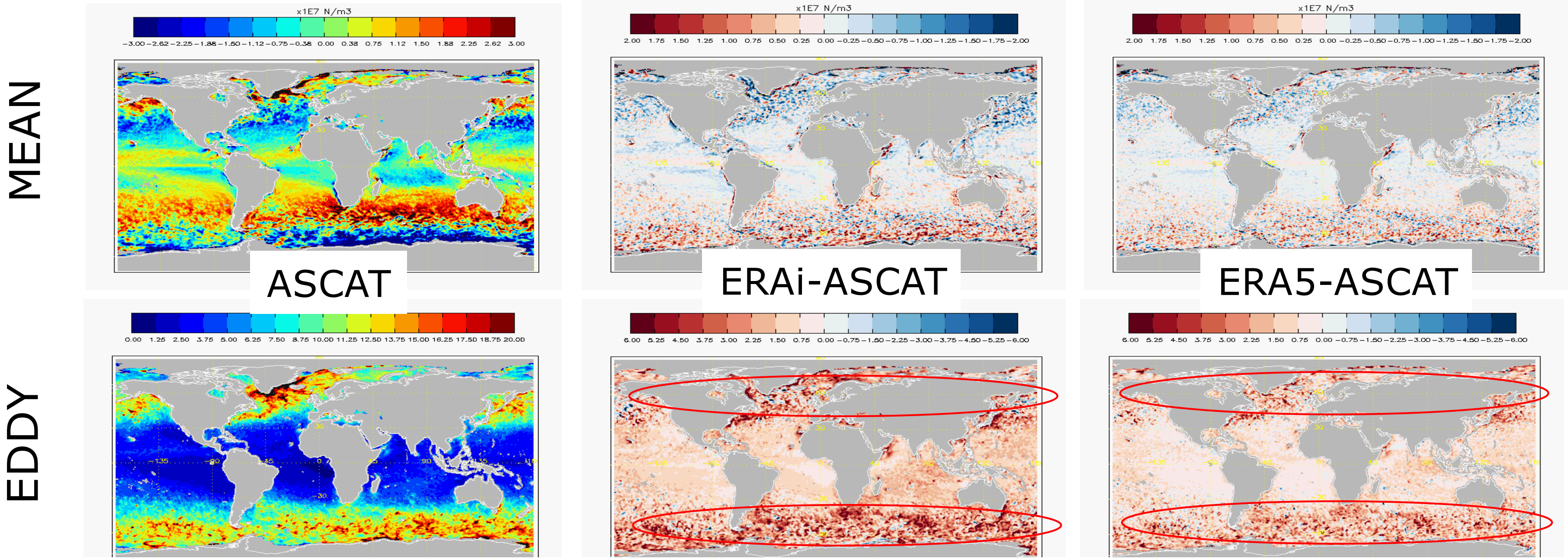
ERA5 - ASCAT

- → Defective model convergence along ITCZ, weak Pacific cold tongue divergence
- → Missing model mean divergence (subsidence) over subtropics (red)
- → Missing model mean convergence over subpolar area (blue)
- → Lacking tropical moist convection in eddy divergence

Belmonte & Stoffelen, 2019

Wind Stress Curl

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu



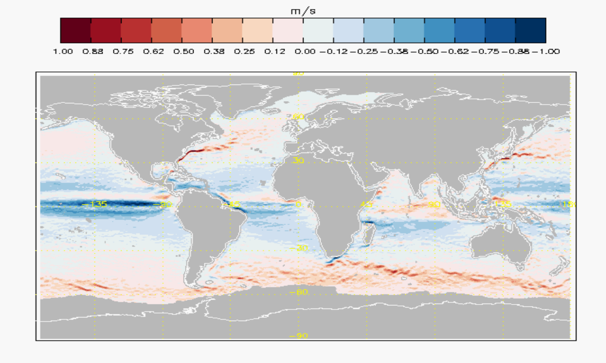
- → ERA mean stress curl is **more cyclonic** (blue NH, red SH) at high latitudes
- → May be caused by defective poleward meridional transport
- → Associated to low eddy stress curl activity → missing mesoscale turbulence
- → **This has obvious implications for Ekman upwelling estimates**

Belmonte & Stoffelen, 2019

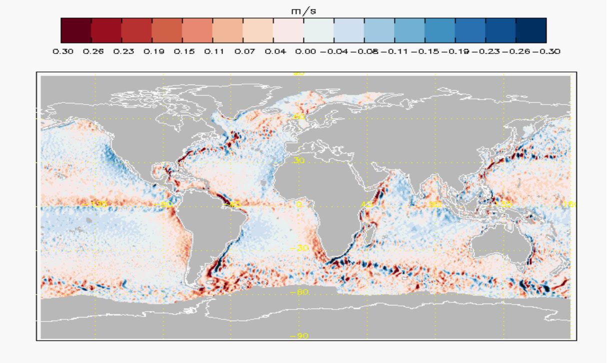
Effect ocean currents

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

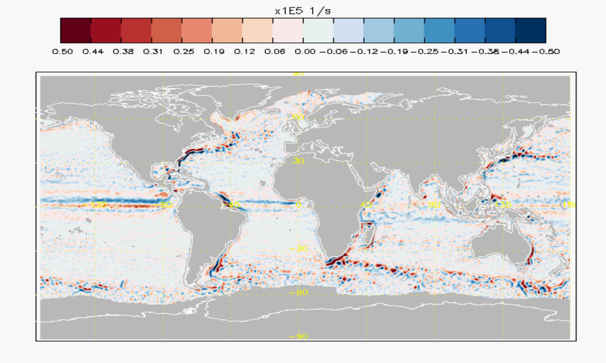
Copernicus Globcurrent



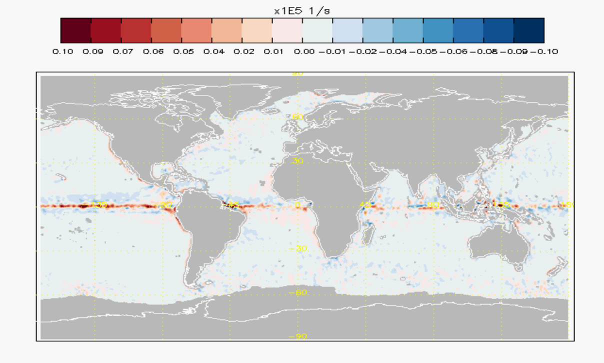
Mean zonal



Mean meridional



Vorticity

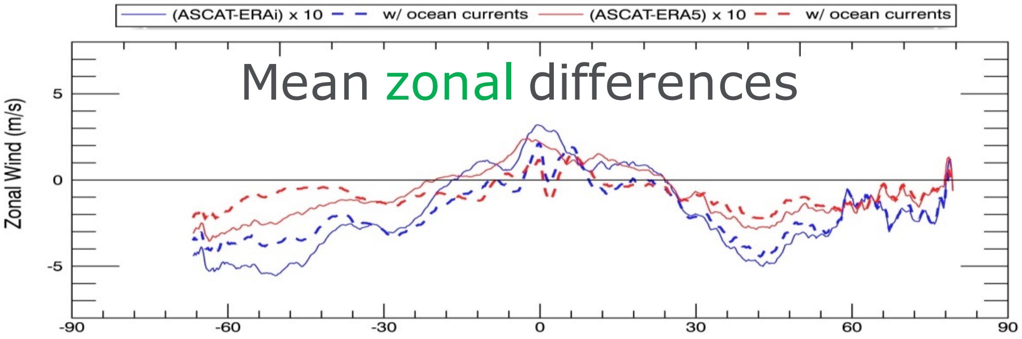


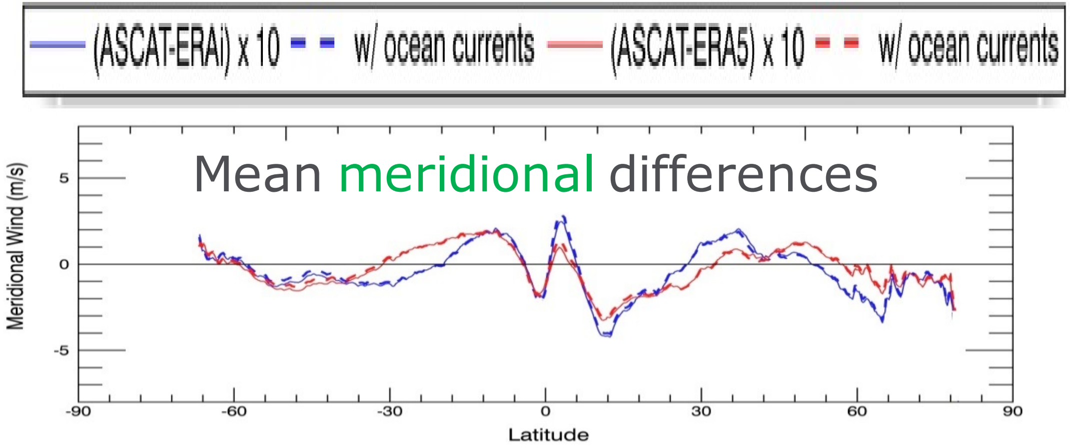
Divergence

Effect of Globcurrent

→ Globcurrent notably relieves the zonal wind biases

→ Globcurrent has no effect on the smaller meridional wind biases


Mean zonal differences

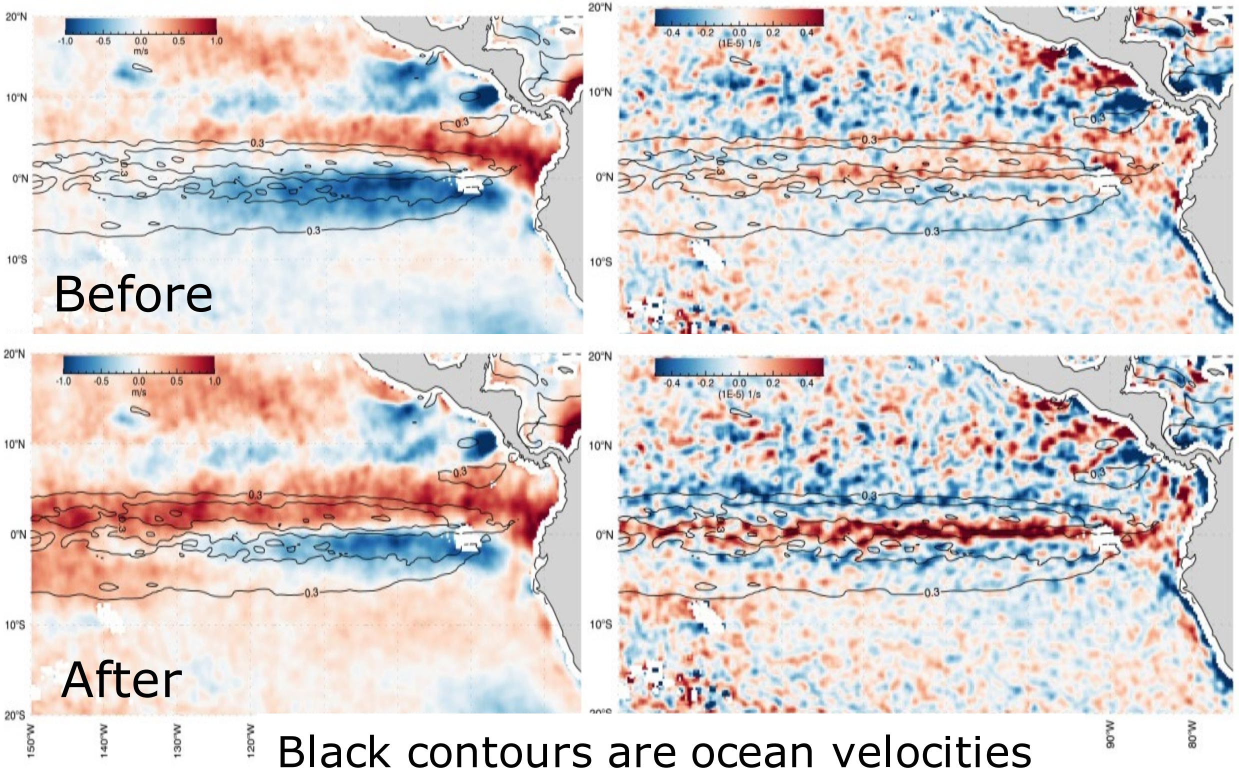

Mean meridional differences

Belmonte & Stoffelen, 2019

Effect of Globcurrent

Eastern Tropical Pacific

- → Globcurrent accentuates SST effects in ASCAT winds that are missing in ECMWF winds
- → Provides much better alignment of ECMWF discrepancies with branched SEC (N and S) to show positive curl error in between



Black contours are ocean velocities

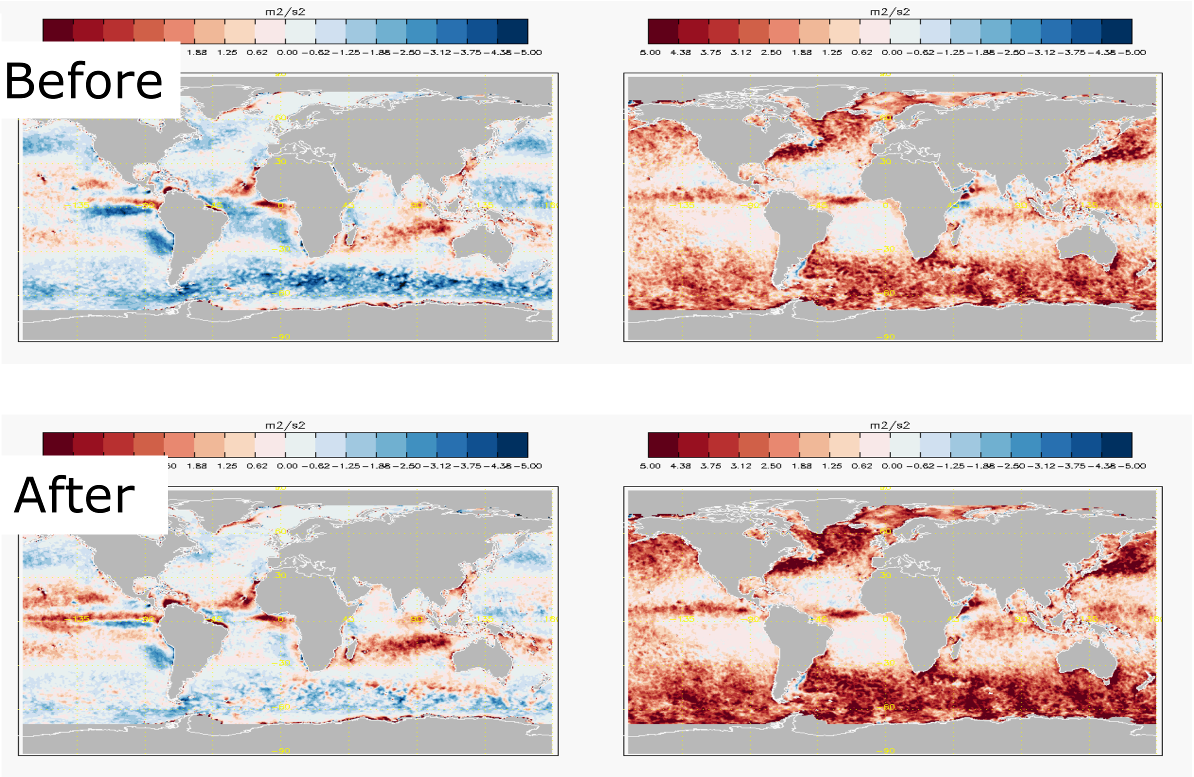
Mean wind speed differences to ERA5

Mean wind stress curl differences to ERA5

Belmonte & Stoffelen, 2019

Effect of Globcurrent

- → Reduces MKE differences in the mid-latitudes, but more red in tropics
- → EKE differences increase globally, particularly in the extra-tropics
- → Globcurrent mesoscales add variability to ASCAT differences
- → Local wind-related drifts are both in ASCAT and Globcurrent: double penalty



MKE differences EKE differences

Belmonte & Stoffelen, 2019

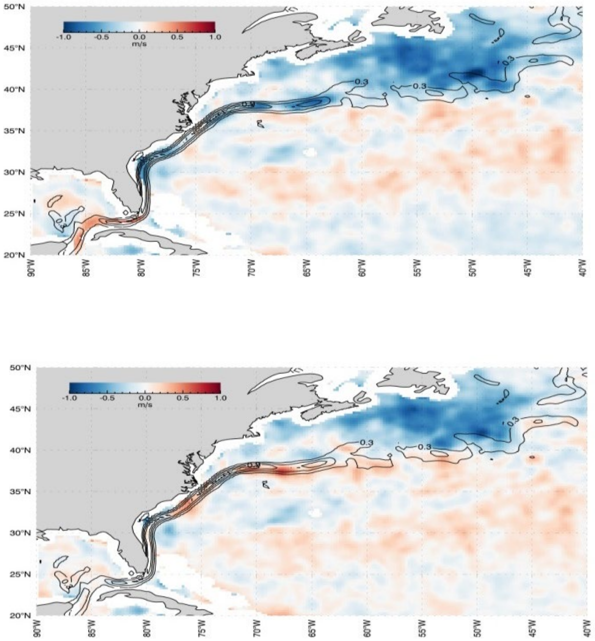
Effect of Globcurrent

Gulf Stream

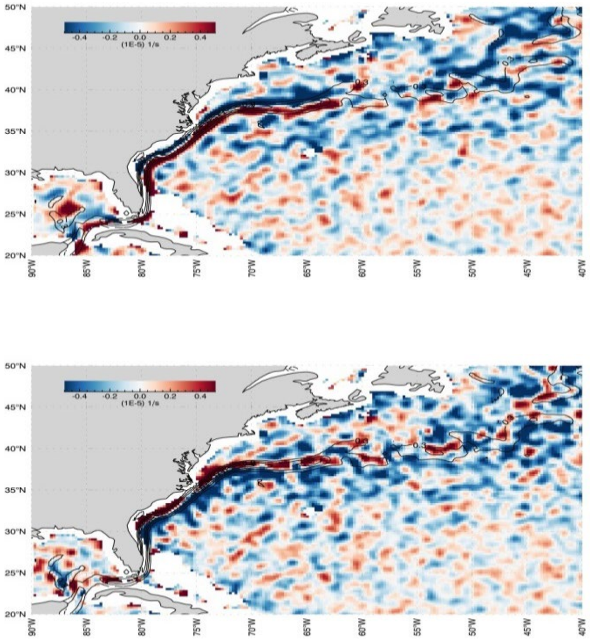
Before

Contours are ocean velocities

After the correction



Mean wind speed differences to ERA5



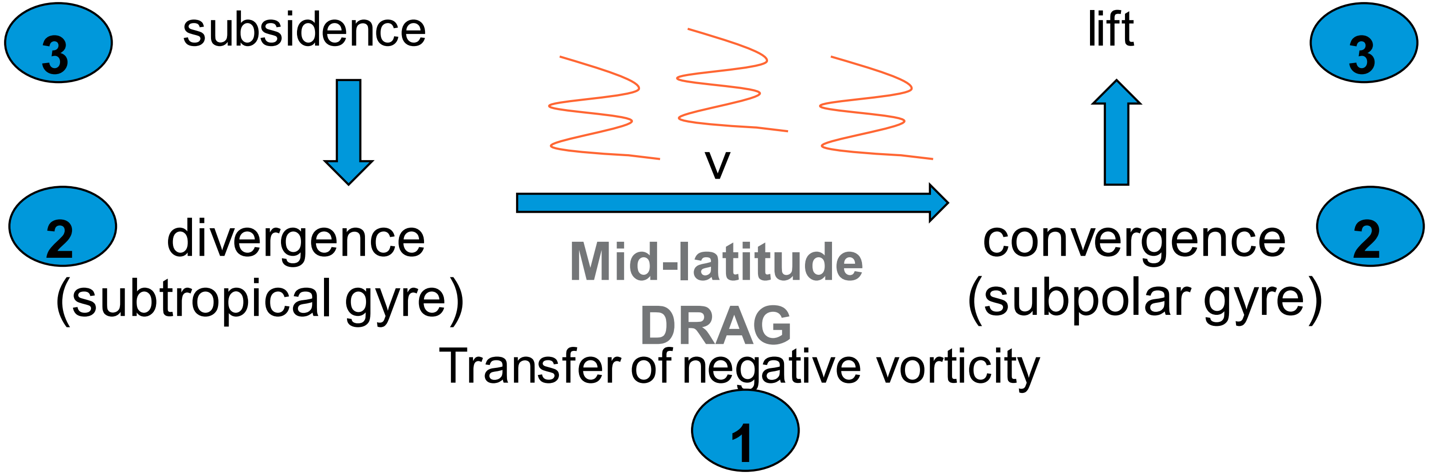
Mean stress curl differences to ERA5

Belmonte & Stoffelen, 2019

Error Mechanism ?

At **mid-latitudes**, <u>missing wind variability in ERA</u> can be associated to:

- Excess zonal mean model winds and defective poleward flows
- Excess cyclonic stress curl
- Defective subtropical divergence and defective subpolar convergence



3 subsidence

lift 3

v

2 divergence
(subtropical gyre)

Mid-latitude DRAG

convergence 2
(subpolar gyre)

Transfer of negative vorticity

1

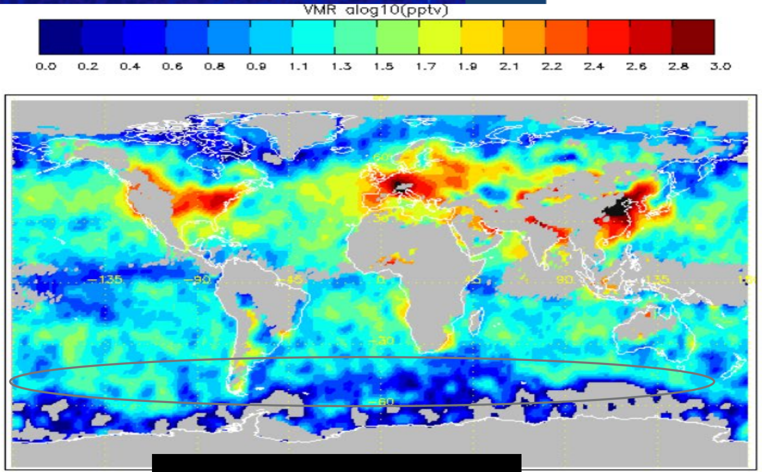
→ Missing 3D turbulence weakens (poleward) flow in Ferrel Cell
→ Ocean forcing implications?

Belmonte Rivas & Stoffelen, 2019

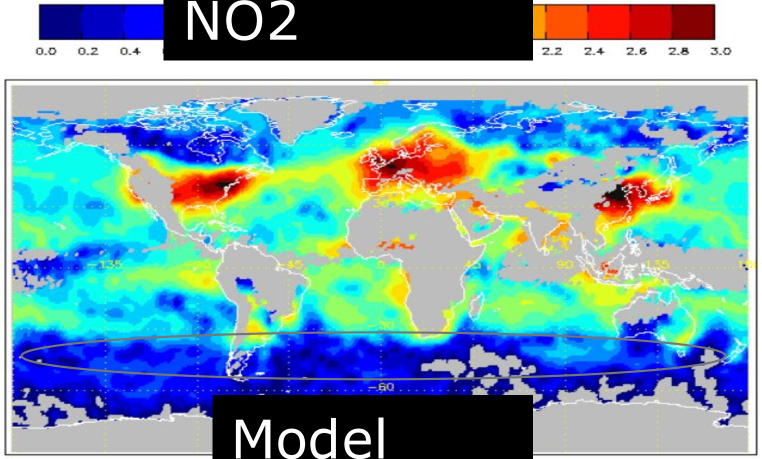
Ancillary slides

The geographical distribution of model vs observed NO2 below 820 hPa (land source are urban emissions in US, Europe and China) suggest that horizontal diffusion by model winds (ERA Interim) is not vigorous enough…

[Belmonte et al, OMI tropospheric NO2 profiles, ACP, 2015]



Observed NO2

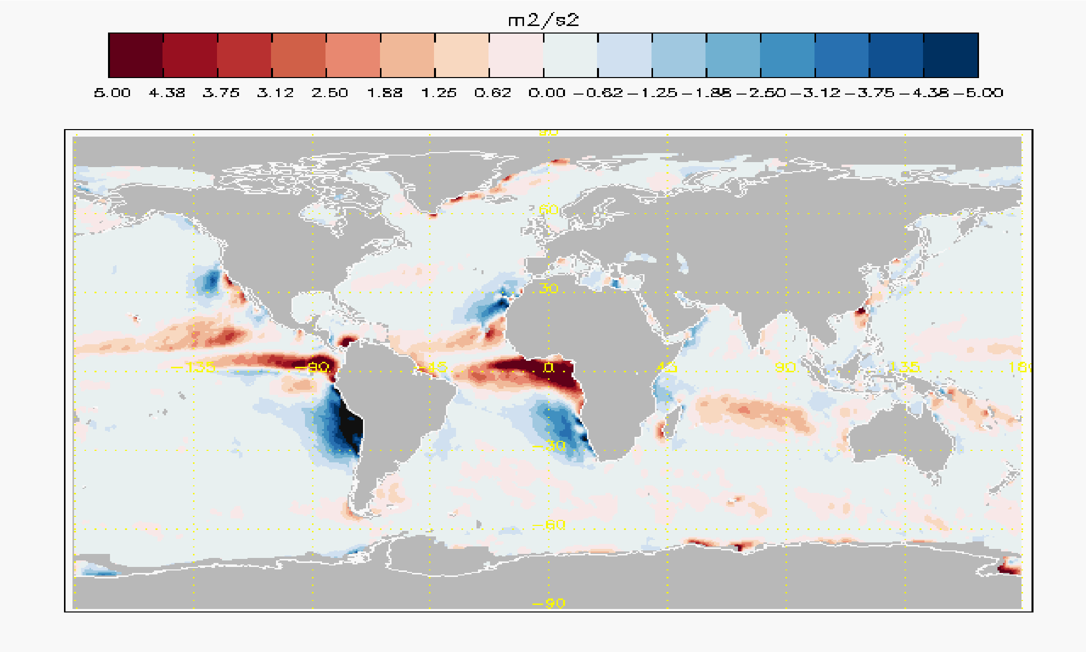


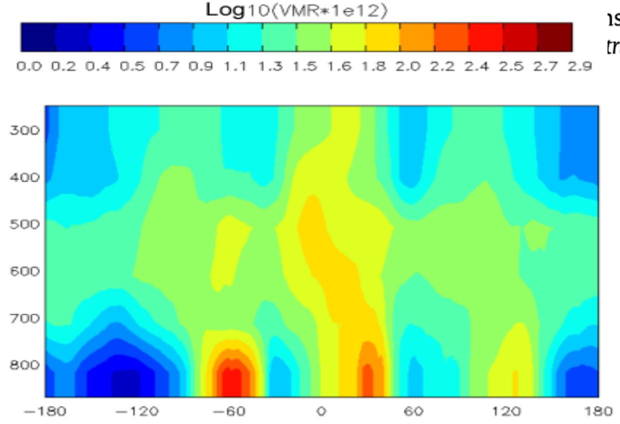
Model NO2

ds
ituut
ctuur en Milieu

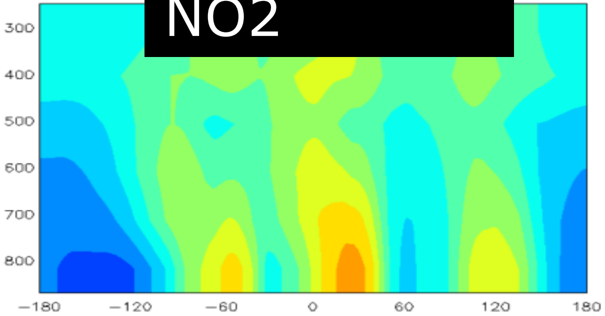
Departures in meridional mean kinetic energy

ASCAT minus ERA interim
2012





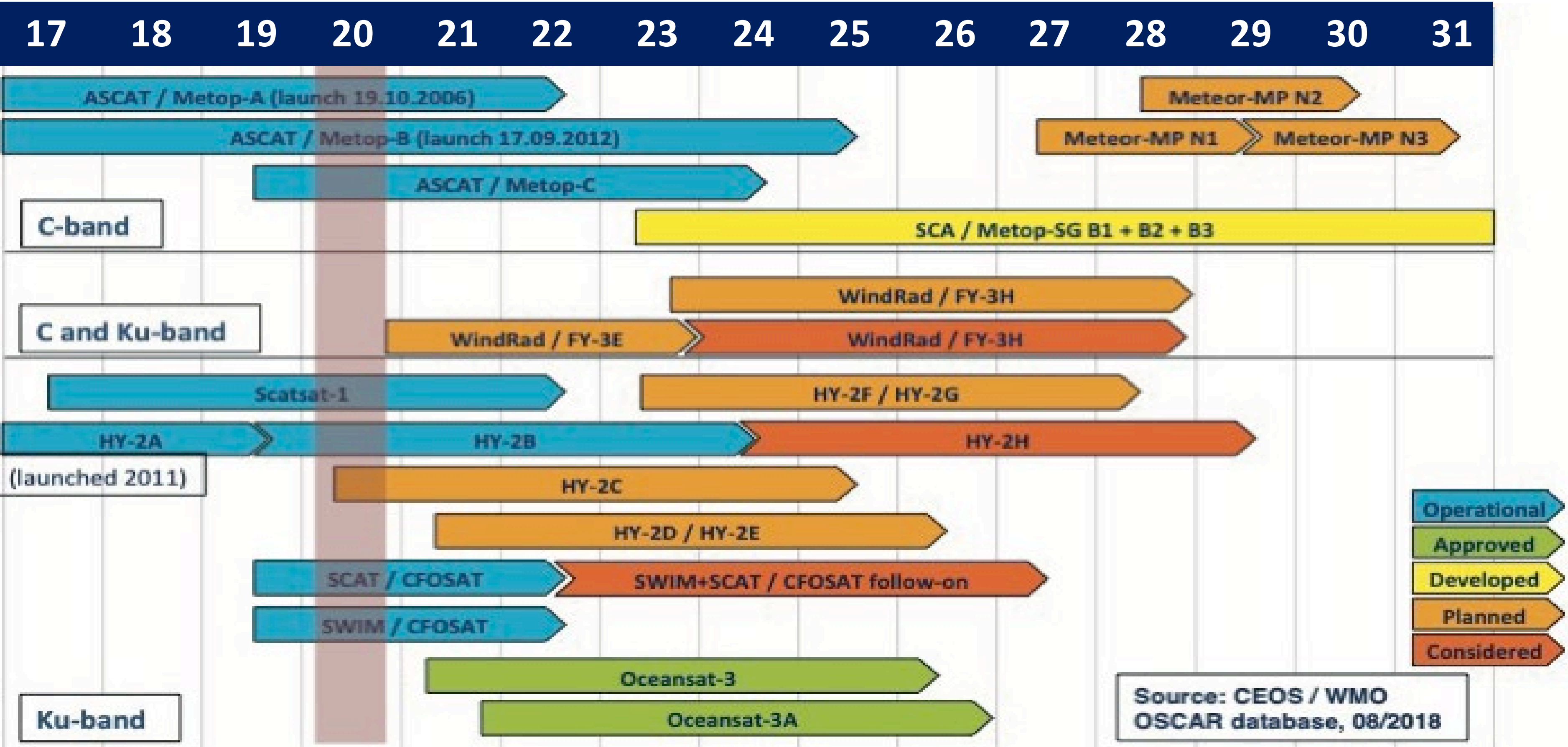
Observed NO2



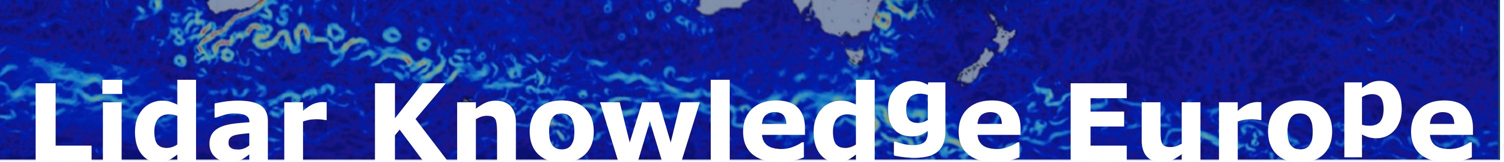
Model NO2

Scatterometer golden age

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu



Source: CEOS / WMO
OSCAR database, 08/2018



Lidar Knowledge Europe

LIKE

Innovative Training Network

1) Optical remote sensing lidar in wind tunnels
2) Improve wind lidars for wind energy
3) Development of an uncertainty model for modular wind lidar designs
4) Floating lidar to assess offshore wind resources
5) Computational flow models for lidar field campaigns
6) Aeolus satellite lidar for wind mapping
7) Lidar for tall wind for Kitemill
8) Wind turbine wake characterization with long-range lidars
9) Lidar measurements of intra wind farm wake dynamics
10) Characterization of power performance of a wind turbine inside a wind farm
11) Adaptive lidar control
12) Atmospheric turbulence characterization under inhomogeneous inflow conditions using nacelle-lidar measurements
13) Lider applied for planning and design of long-span bridges
14) Lidar-assisted wind farm control in wind tunnel and full scale
15) Turbulence characterization at exposed airports

Lidar Knowledge Europe

Innovative Training Network

Aeolus

1) Verification of PBL winds by triple collocation
2) Verification of PBL modification by Aeolus OSE
3) Aeolus data assimilation near hurricanes

Haichen Zu