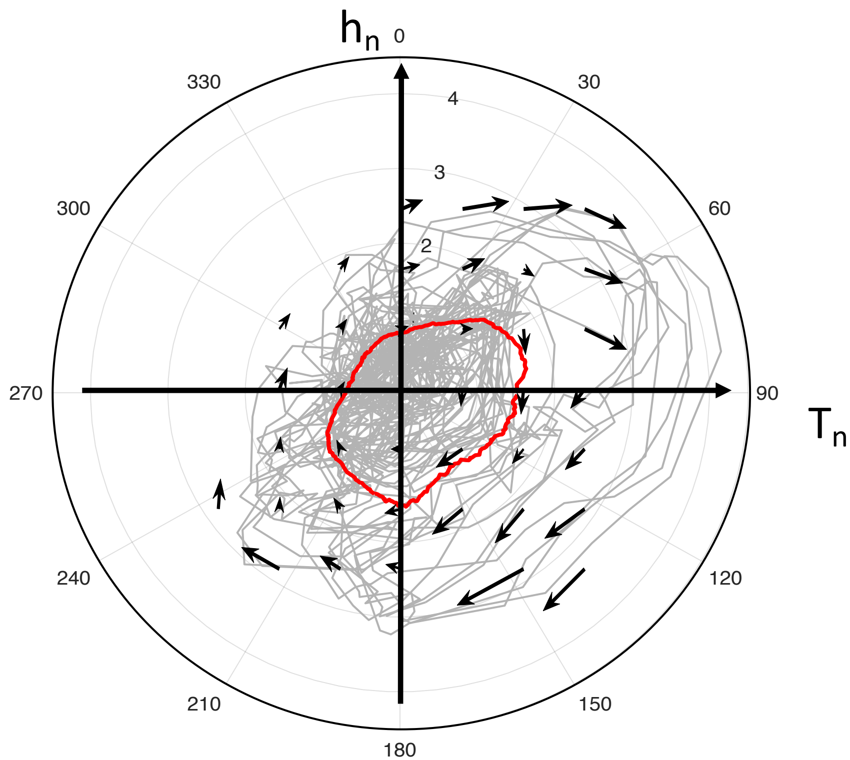
Asymmetries in the ENSO phase space



Dietmar Dommenget and Maryam Al-Ansari

submitted to Climate Dynamics

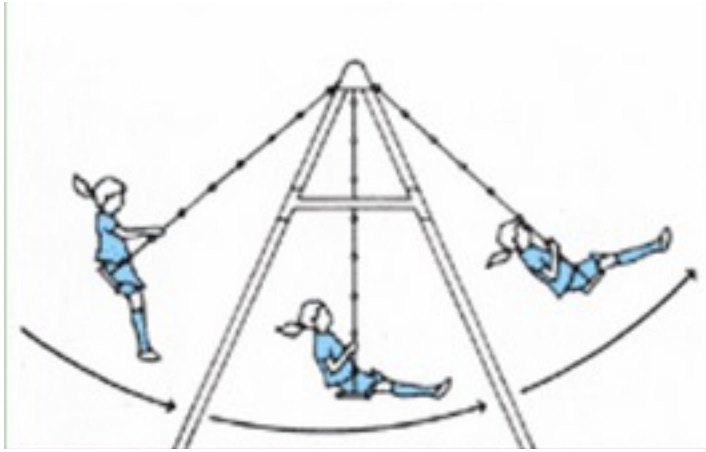
MONASH University

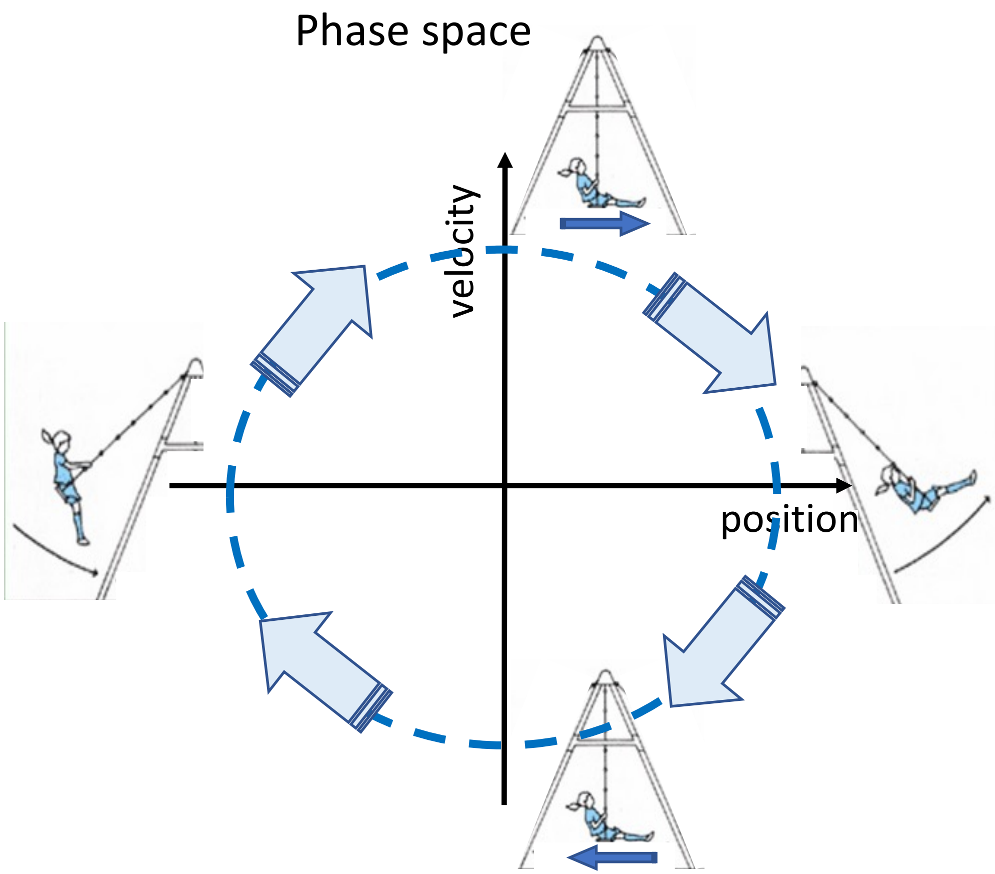
climate extremes
ARC centre of excellence

overview

- ❖ Motivation
- ❖ The ENSO phase space
- ❖ Observed ENSO phase space
- ❖ Linear & Non-linear Recharge Oscillator
- ❖ Predictions

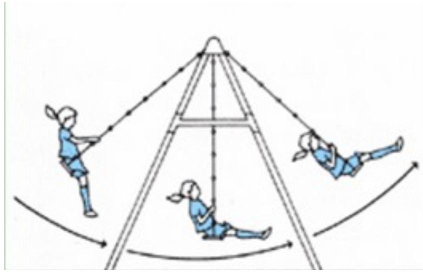
The physical phase space

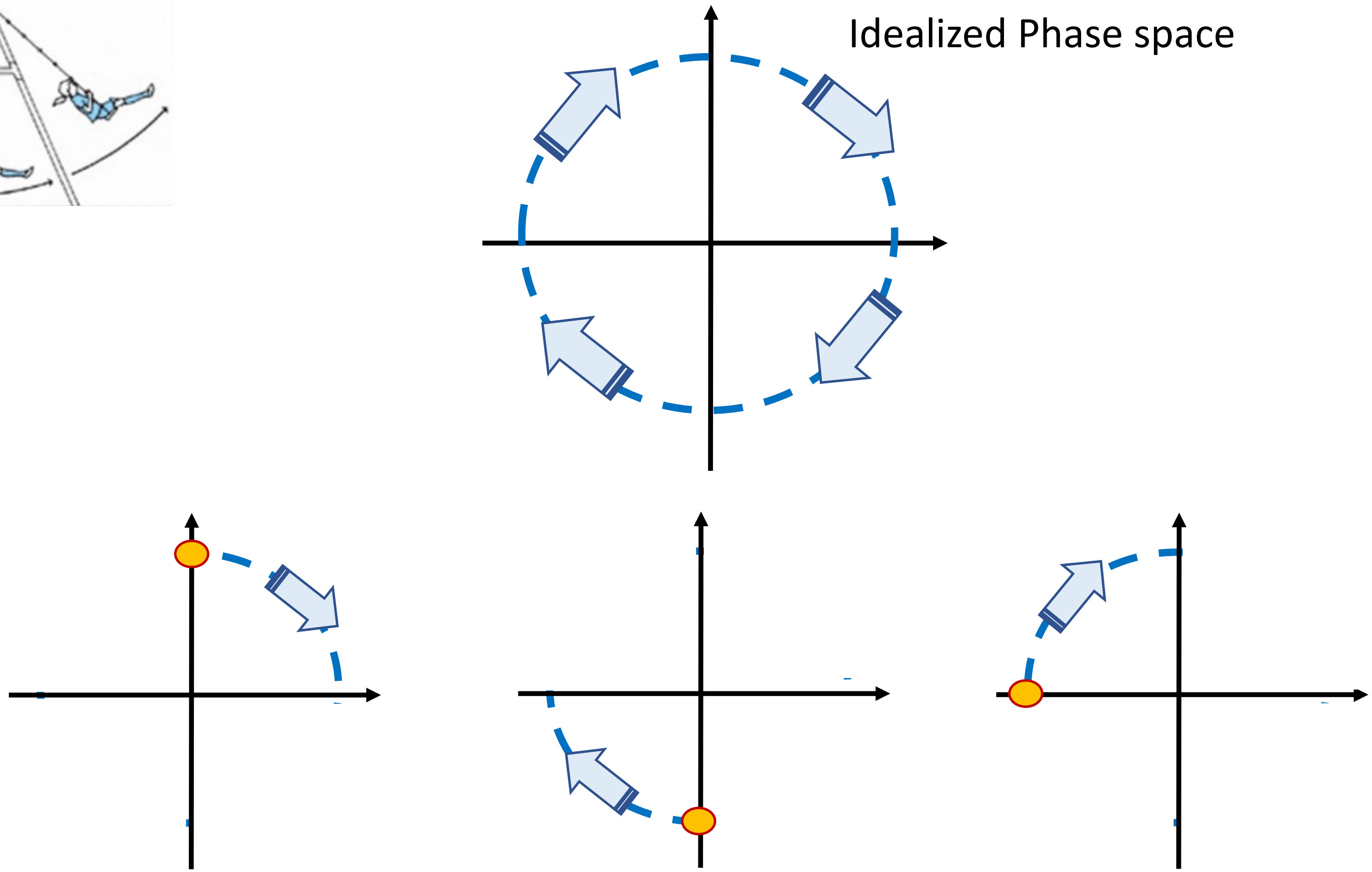




- The physical phase space illustrates an oscillation.
- It presents the system as a cycle.

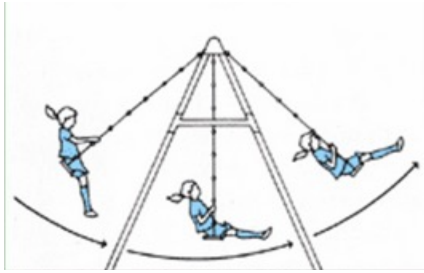
The physical phase space

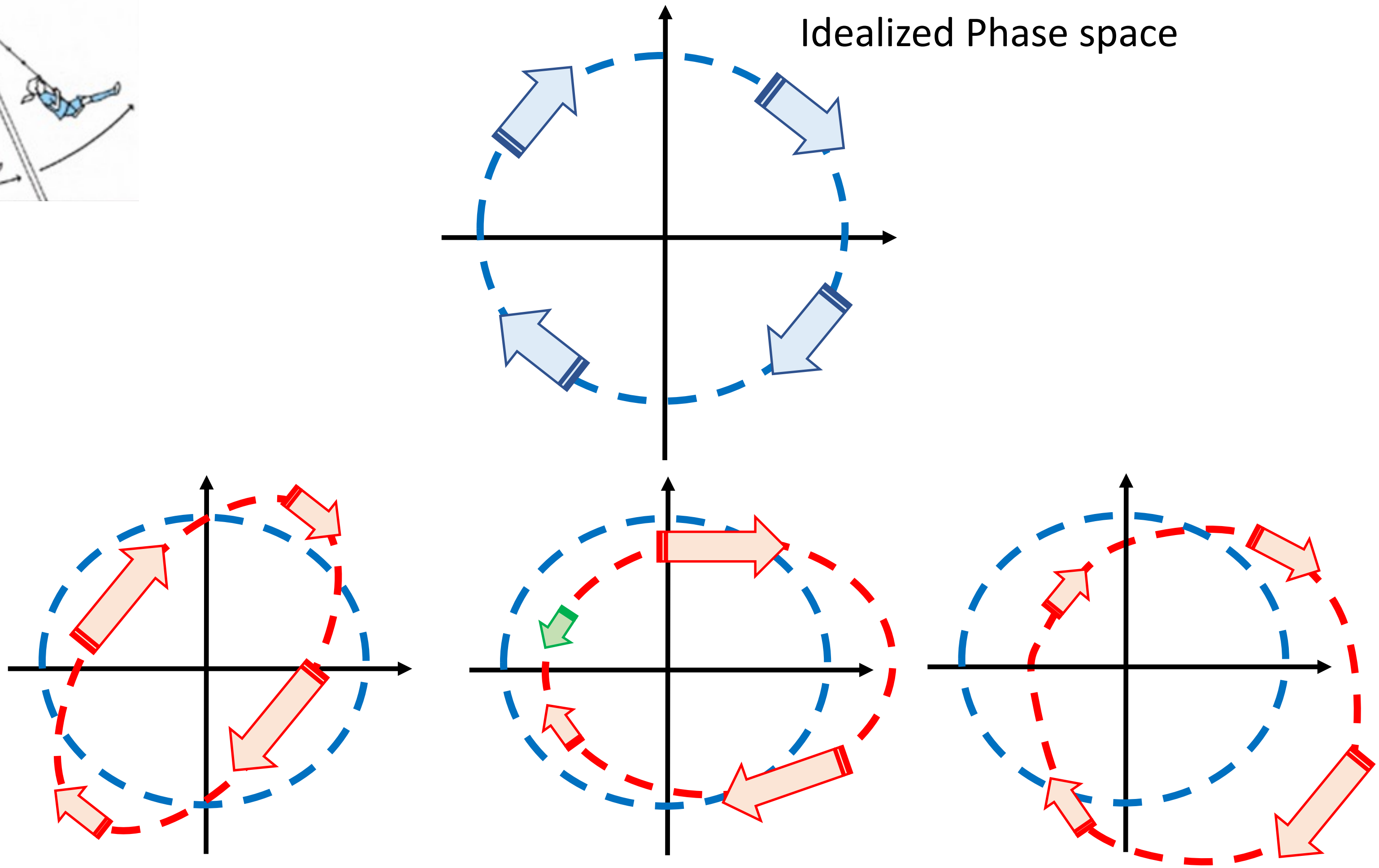




❖ A cycle with clear tendencies implies predictability

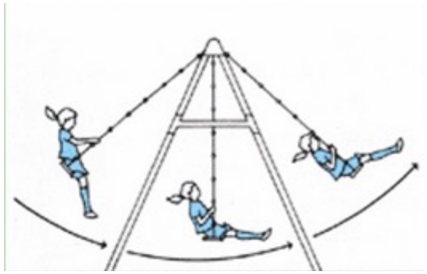
The physical phase space

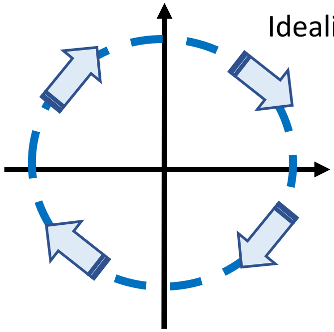




- Deviations from a perfect cycle indicate interesting dynamics

The physical phase space





What is a Climate Mode?

- ❖ A Physical climate mode has a phase space with two variables x and y with an out-of-phase relationship
- ❖ The mode has clear propagation through all phase of the cycle in clockwise direction
- ❖ This is the essence of a predictable oscillator

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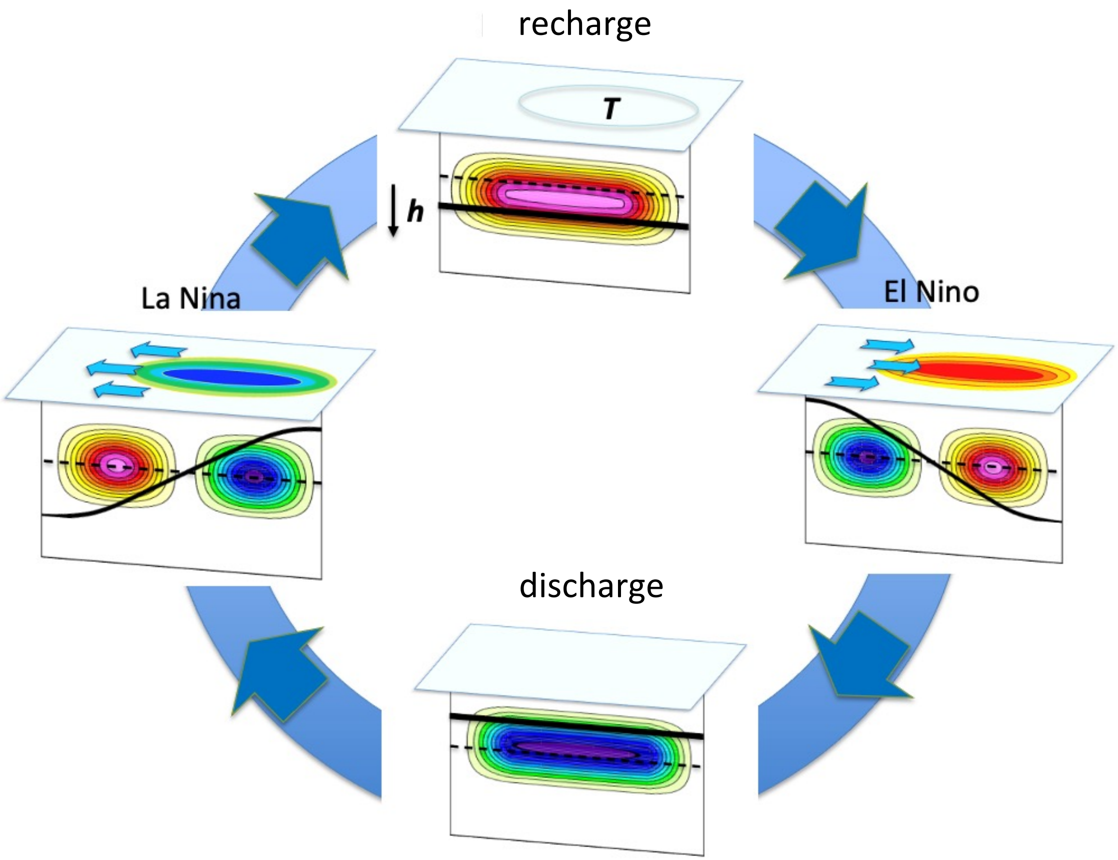
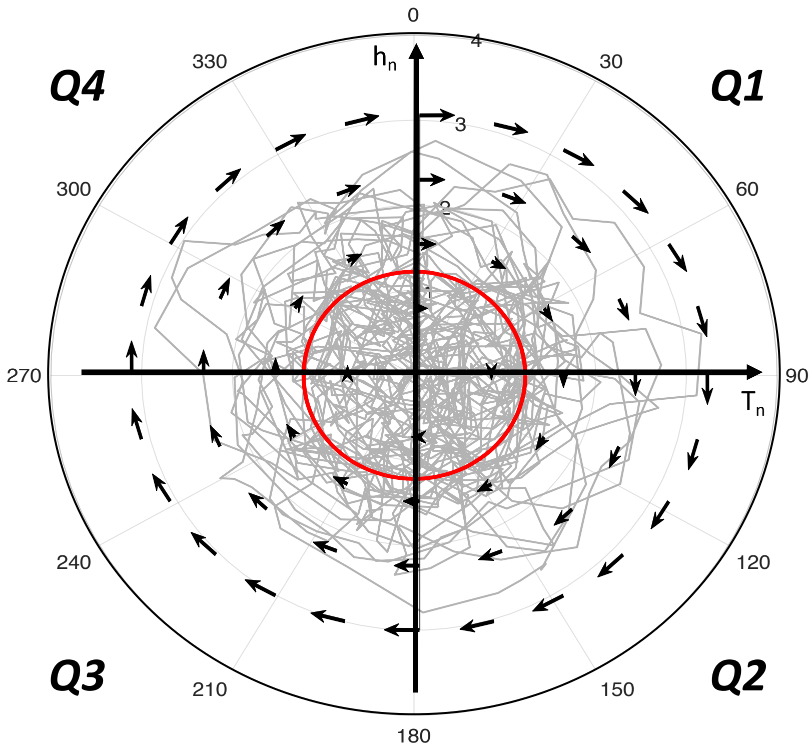
The ENSO phase space



- The ENSO phase space is based on the ***Recharge Oscillator*** model of ENSO
- A cycle between upper ocean heat content (thermocline depth; ***h***) and SST (***T***)

The idealized Recharge Oscillator model



radius = strength (***S***)

angle = phase

— = 100yrs sample of ***T*** and ***h***

— = mean ***S*** as function of phase

→ = mean tendencies

$$\frac{dT(t)}{dt} = a_{11}T(t) + a_{12}h(t) + Rt$$

$$\frac{dh(t)}{dt} = a_{21}T(t) + a_{22}h(t) + Rh$$

a_{11}, a_{22} = damping/growth rate

a_{12}, a_{21} = delayed negative feedback (coupling)

Rt, Rh = noise forcing

Idealized: $a_{11} = a_{22}$ $a_{12} = -a_{21}$ Rt = Rh

integrate stochastic model for 10^4yrs of ***T*** and ***h*** statistics

❖ The idealized ***Recharge Oscillator*** model is symmetric / all phase are the same

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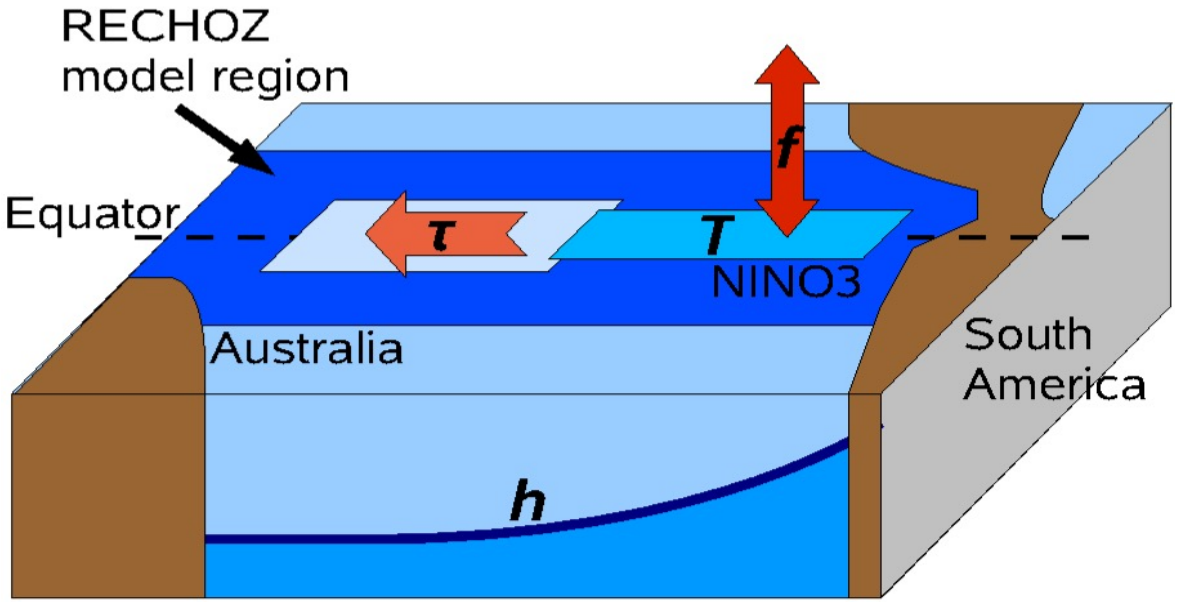
The observed ENSO phase space



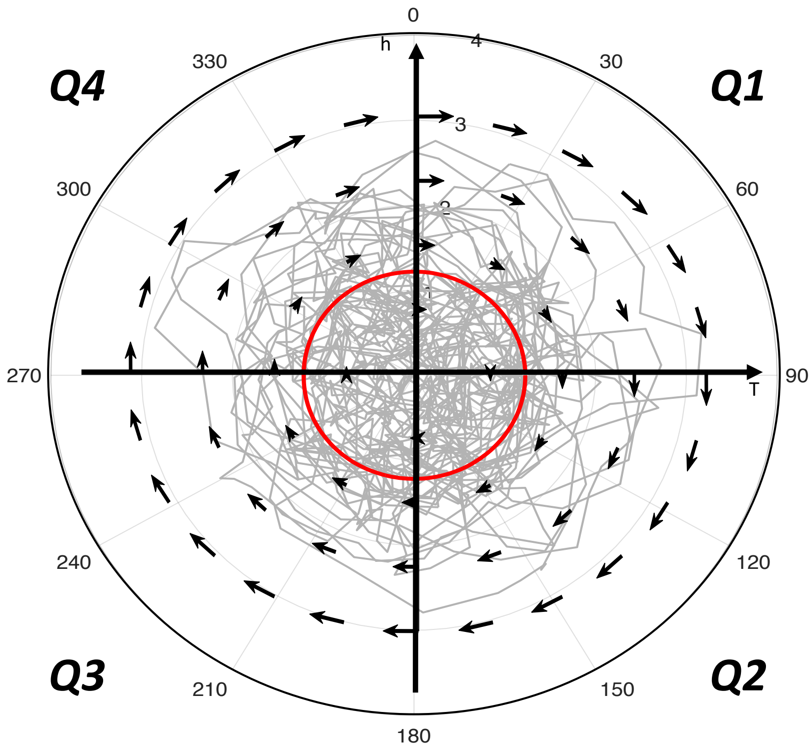
T = NINO3 SST anomalies

h = Z20 isotherm of whole eq. Pacific

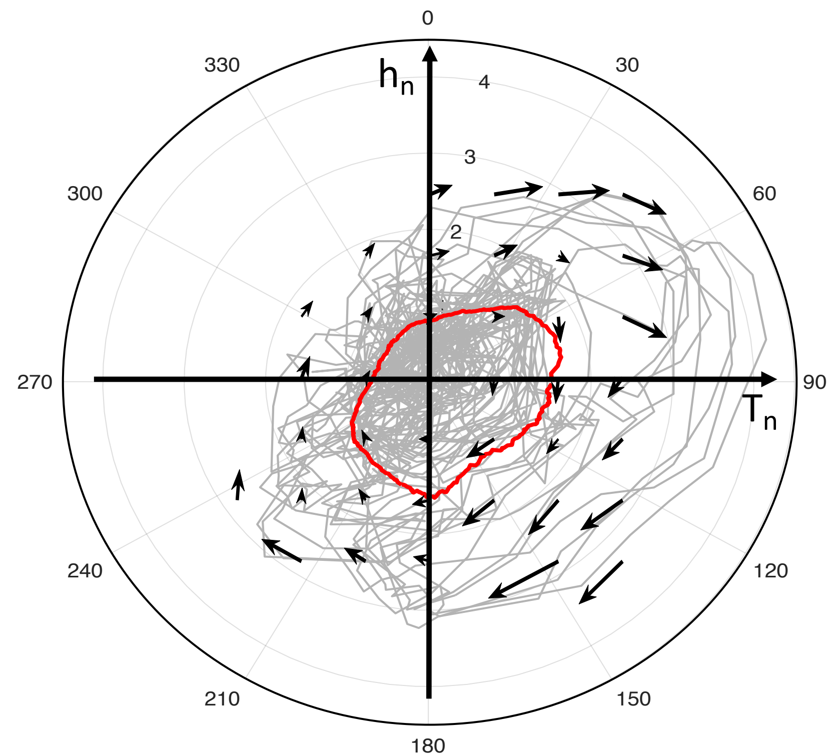
Data: combined TAO-observations, ocean reanalysis (SODA, CHOR-RL/AS) ***1980-2015***

The observed ENSO phase space

idealized ***Recharge Oscillator***



Observed ***T*** and ***h***



radius = strength (***S***)

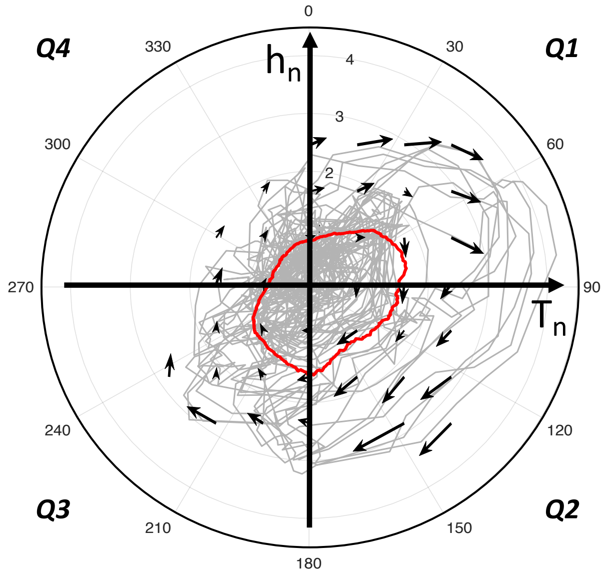
angle = phase

= mean ***S*** as function of phase

= mean tendencies

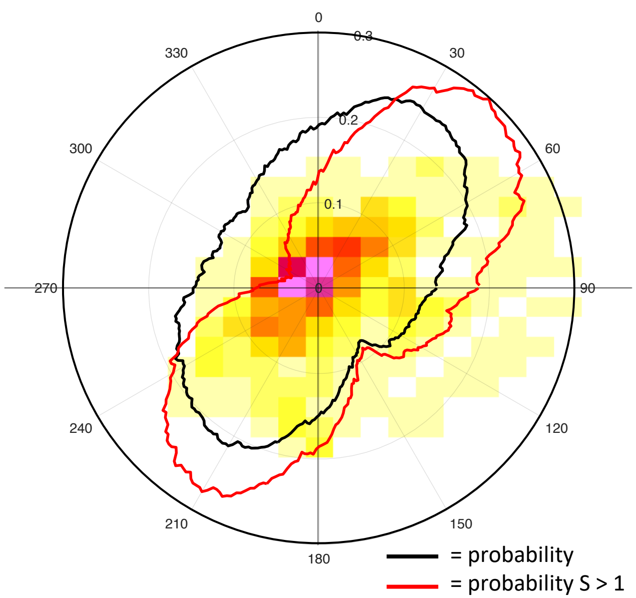
- The observed ENSO phase space has strong asymmetries.
- Both in ***probabilities*** and in ***tendencies***

The observed ENSO phase space



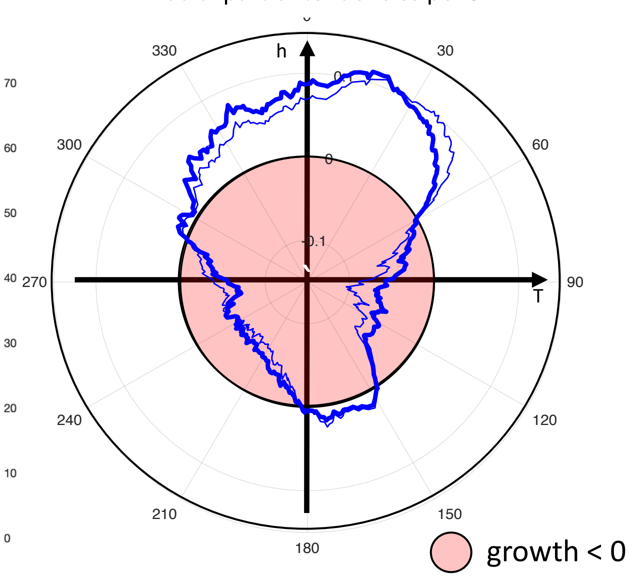
- probabilities are shifted away from Q4.
- growth rate is largest in the recharge state and negative during El Nino / La Nina
- Phase transition is fastest after El Nino and close to zero during La Nina states.

probability distribution



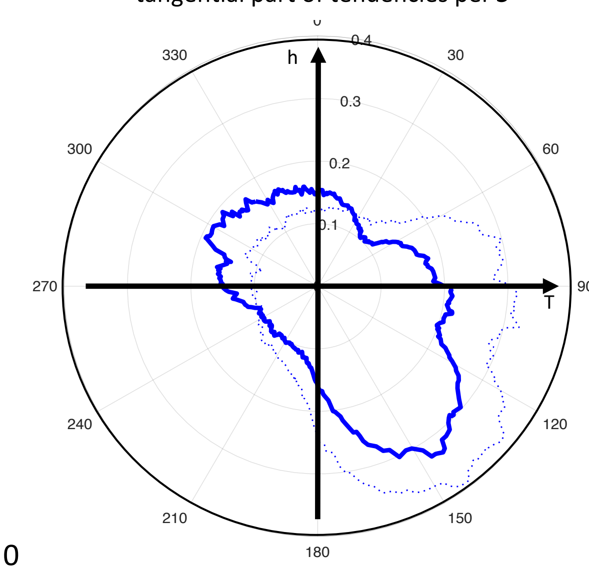
growth rate (1/mon)

radial part of tendencies per ***S***



Phase speed (1/mon)

tangential part of tendencies per ***S***



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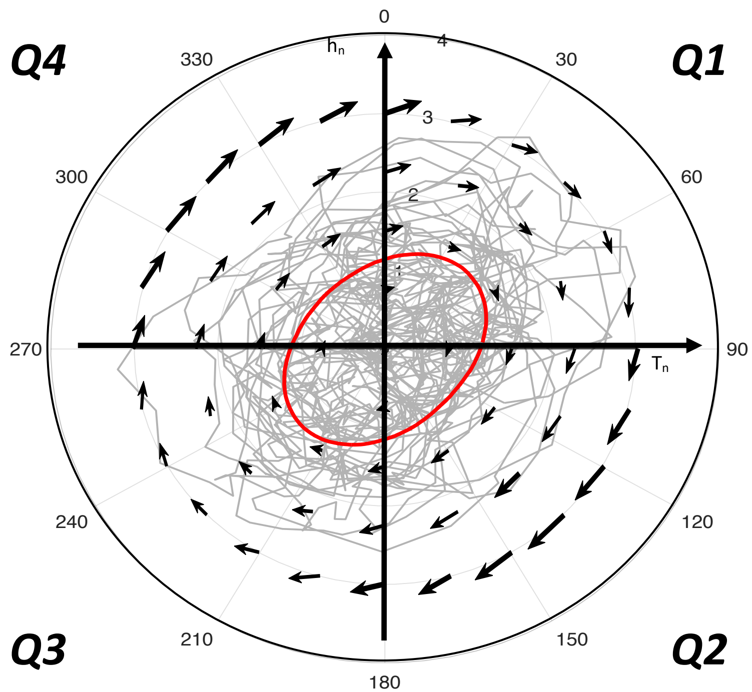
Recharge Oscillator model

*Use **linear** and **non-linear** Recharge Oscillator model to understand observed ENSO phase space asymmetries*

Observed linear Recharge Oscillator model

Observed linear Recharge Oscillator



radius = strength (***S***)
angle = phase
— = 100yrs sample of ***T*** and ***h***
— = mean ***S*** as function of phase
→ = mean tendencies

$$\frac{dT(t)}{dt} = a_{11}T(t) + a_{12}h(t) + Rt$$

$$\frac{dh(t)}{dt} = a_{21}T(t) + a_{22}h(t) + Rh$$

a_{11}, a_{22} = damping/growth rate
a_{12}, a_{21} = delayed negative feedback (coupling)
Rt, Rh = noise forcing

fit to observed ***T*** and ***h***

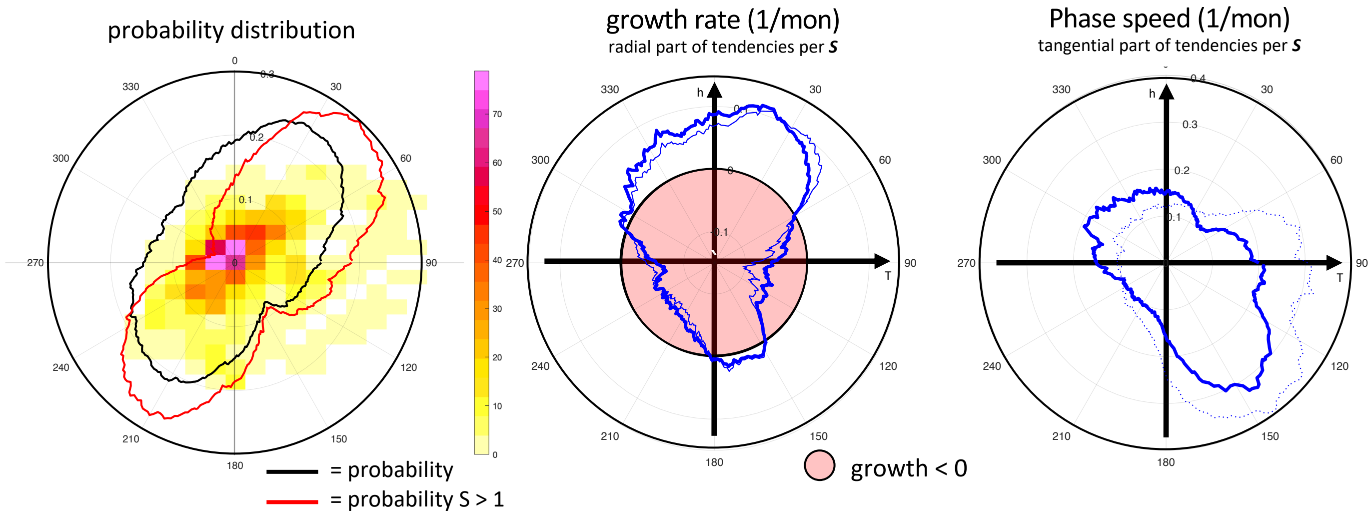
Normalized observed ReOsc model parameters		
$a_{11n} = -0.115\ mon^{-1}$	$a_{12n} = 0.17\ mon^{-1}$	$stdv(\zeta_T) = 0.29\ mon^{-1}$
$a_{22n} = +0.019\ mon^{-1}$	$a_{21n} = -0.16\ mon^{-1}$	$stdv(\zeta_h) = 0.25\ mon^{-1}$

integrate model with white noise forcing for 10^4 yrs.

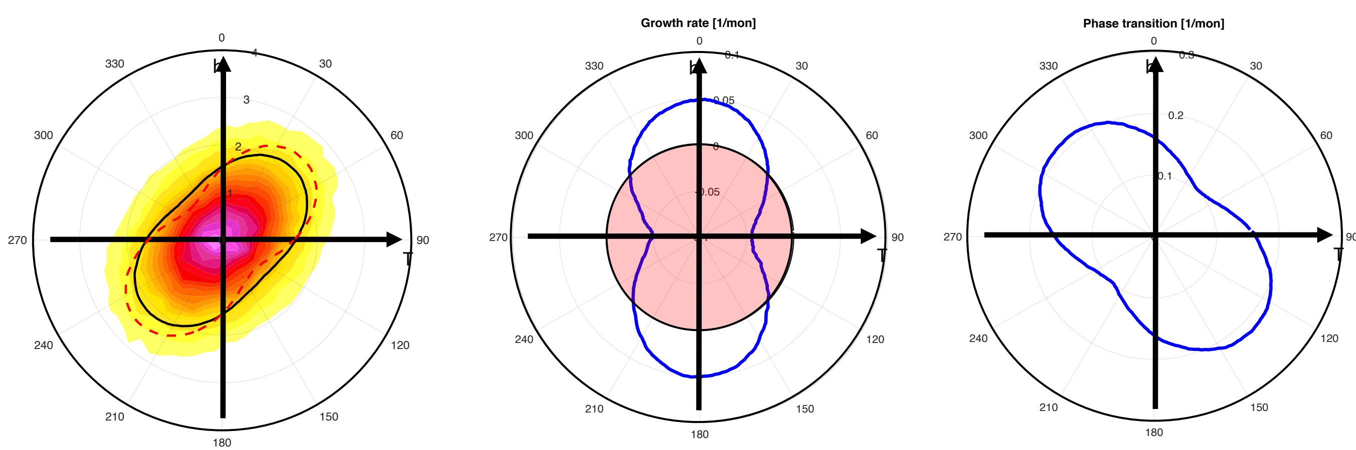
- It is asymmetric in the growth rate ***T*** and ***h***
- It is symmetric in all other parts
- The ENSO phase space is phase-depending

Observed linear Recharge Oscillator model

observed ENSO phase space



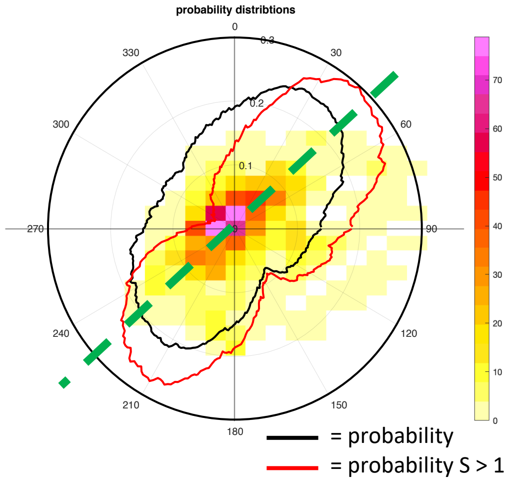
Observed linear Recharge Oscillator



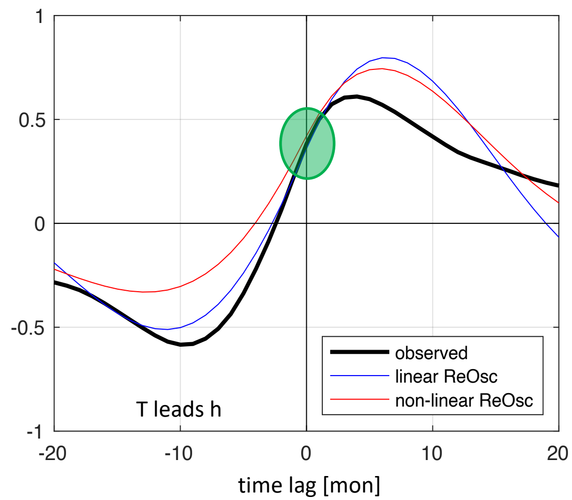
- The linear model can capture some of the phase space characteristics
- It is symmetric for opposite phases
- In-phase correlation between ***T*** and ***h*** explains most of the observed structures
- Some asymmetries are not captured.

Observed Thermocline Depth Estimates

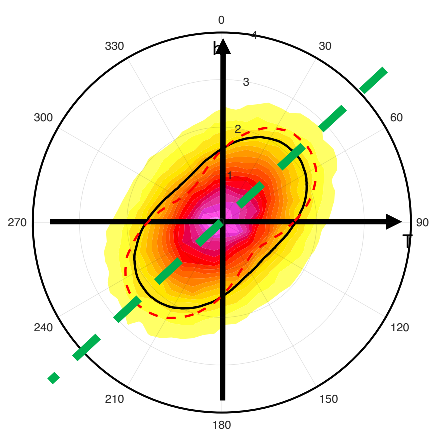
observed ENSO phase space

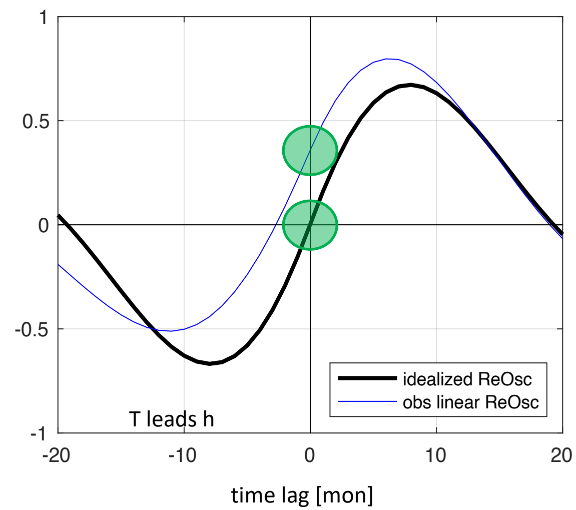


cross-correlation T vs. h



Observed linear Recharge Oscillator

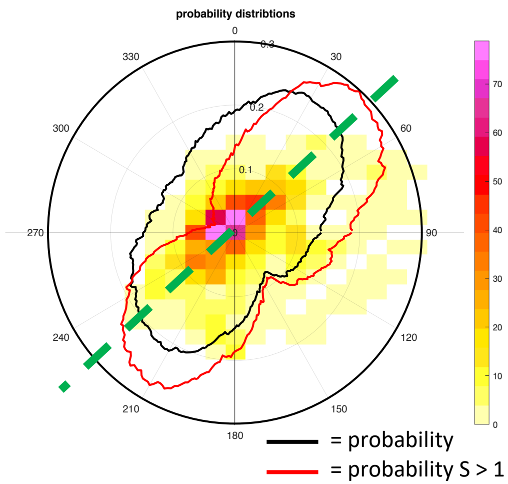




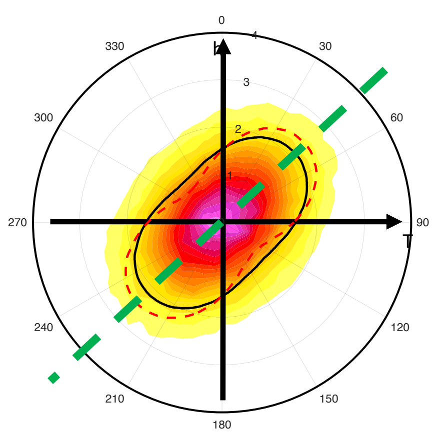
- In-phase correlation between ***T*** and ***h*** explains most of the observed structures
- In ReOsc model growth rates of T/h are strongly asymmetric
- This is not the idea of the ReOsc model
- There is likely a problem with the thermocline estimate (Z20-based)

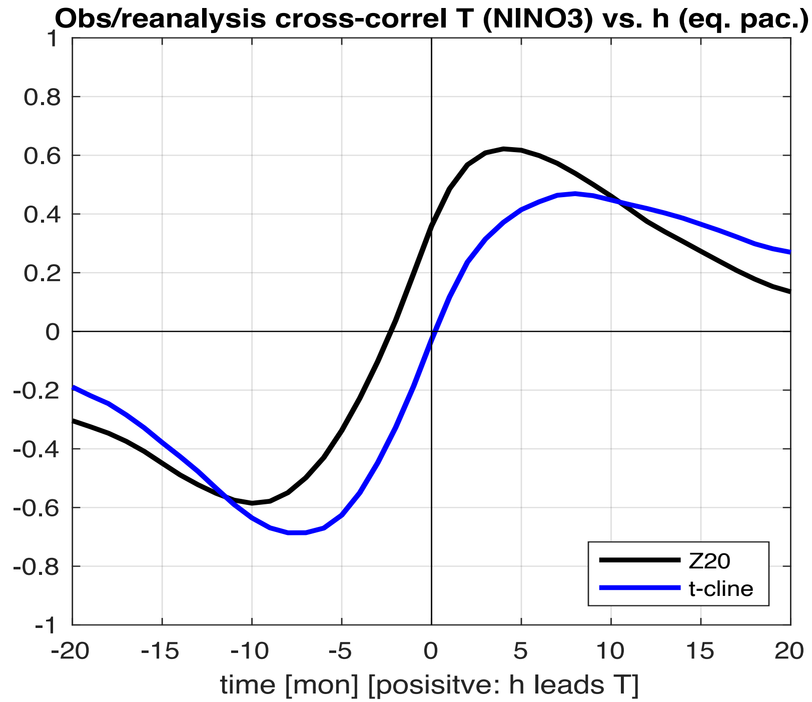
Observed Thermocline Depth Estimates

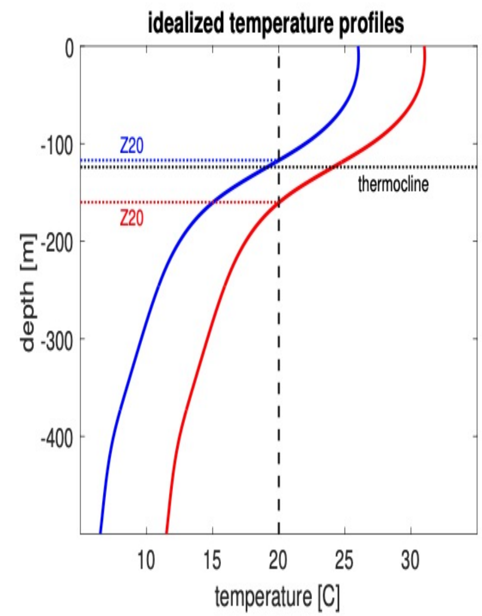
observed ENSO phase space



Observed linear Recharge Oscillator







- ❖ The thermocline depth behaves better in the ReOsc concept than Z20.

A Non-linear Recharge Oscillator model

linear model

$$\frac{dT(t)}{dt} = a_{11}T(t) + a_{12}h(t) + Rt$$

$$\frac{dh(t)}{dt} = a_{21}T(t) + a_{22}h(t) + Rh$$

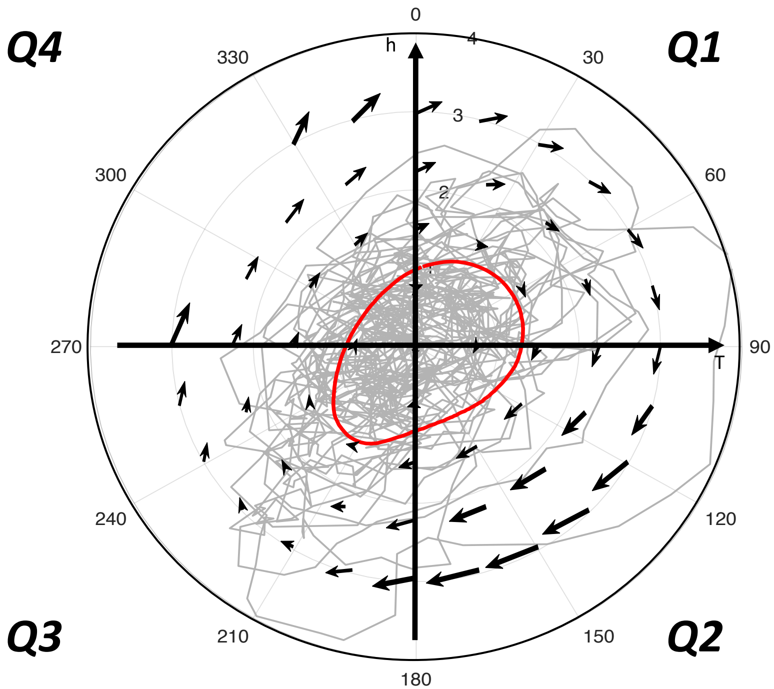
a_{11}, a_{22} = damping/growth rate

a_{12}, a_{21} = delayed negative feedback (coupling)

Rt, Rh = noise forcing

A Non-linear Recharge Oscillator model

Non-linear Recharge Oscillator



radius = strength (***S***)
angle = phase
= 100yrs sample of ***T*** and ***h***
= mean ***S*** as function of phase
= mean tendencies

non-linear model

$$\frac{dT(t)}{dt} = a_{11-2}T^2(t) + a_{11-1}T(t) + a_{11-0} + a_{12}h(t) + Rt$$

$$\frac{dh(t)}{dt} = a_{21}T(t) + a_{22}h(t) + Rh$$

a_{11-0}, a_{11-1}, a_{11-2}, a_{22} = damping/growth rate

a_{12}, a_{21} = delayed negative feedback (coupling)

Rt, Rh = noise forcing

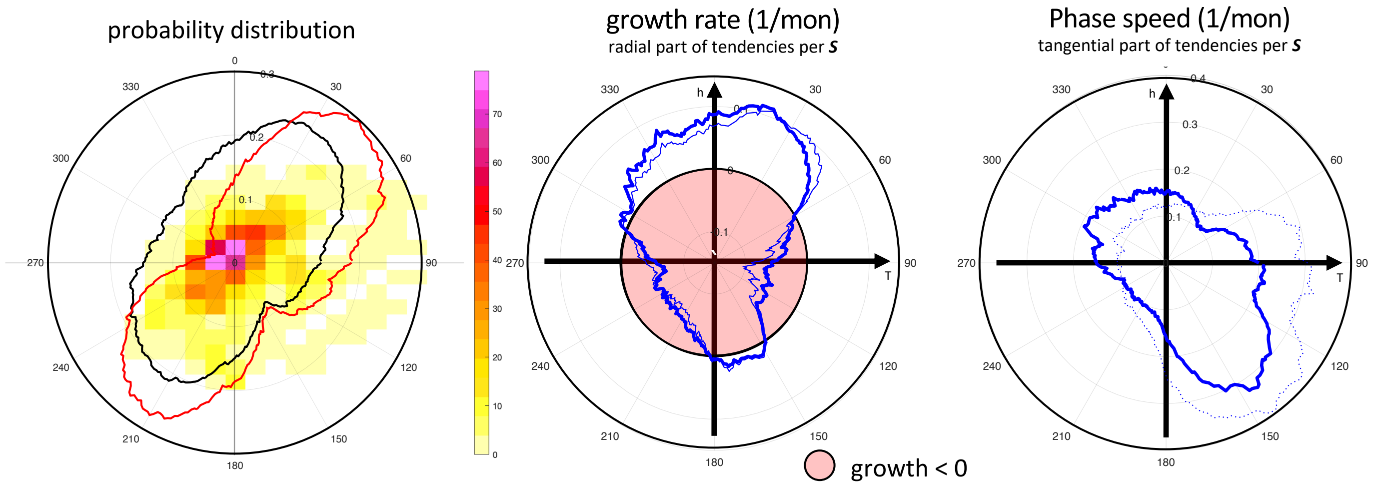
a_{11-0} = -0.035 K mon$^{-1.}$
a_{11-1} = -0.188 mon$^{-1.}$
a_{11-2} = 0.058 K^{-1}mon^{-1}

integrate model with white noise forcing for 10^4 yrs.

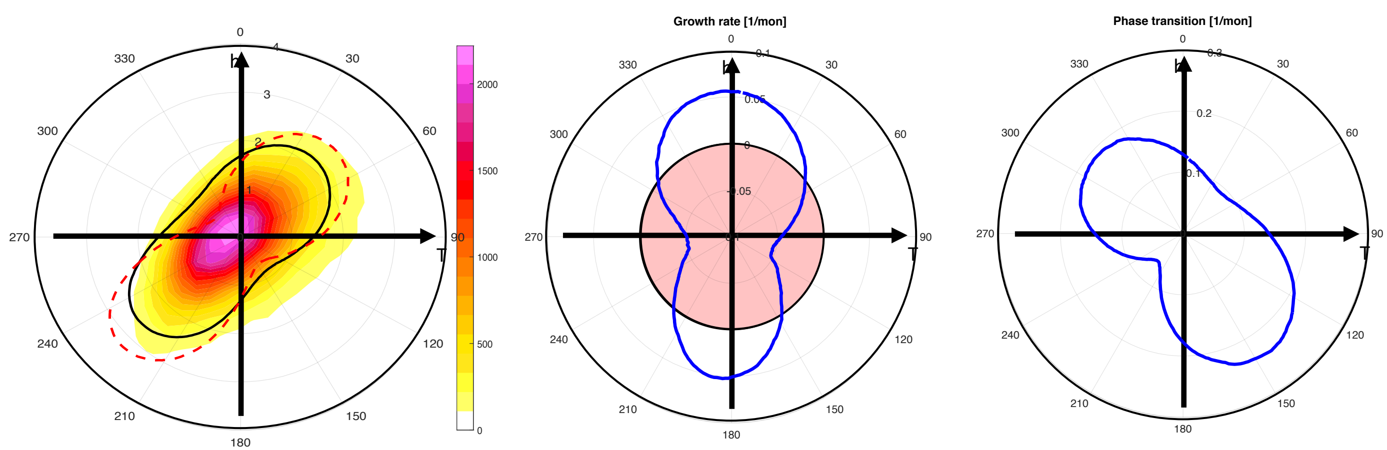
- assume quadratic function for growth of ***T***
- Consistent with non-linear wind-SST (stronger feedback for negative ***T***)

A Non-linear Recharge Oscillator model

observed ENSO phase space



Non-linear Recharge Oscillator



- The non-linear model can capture some of the non-linear characteristics
- Some asymmetries are not captured.

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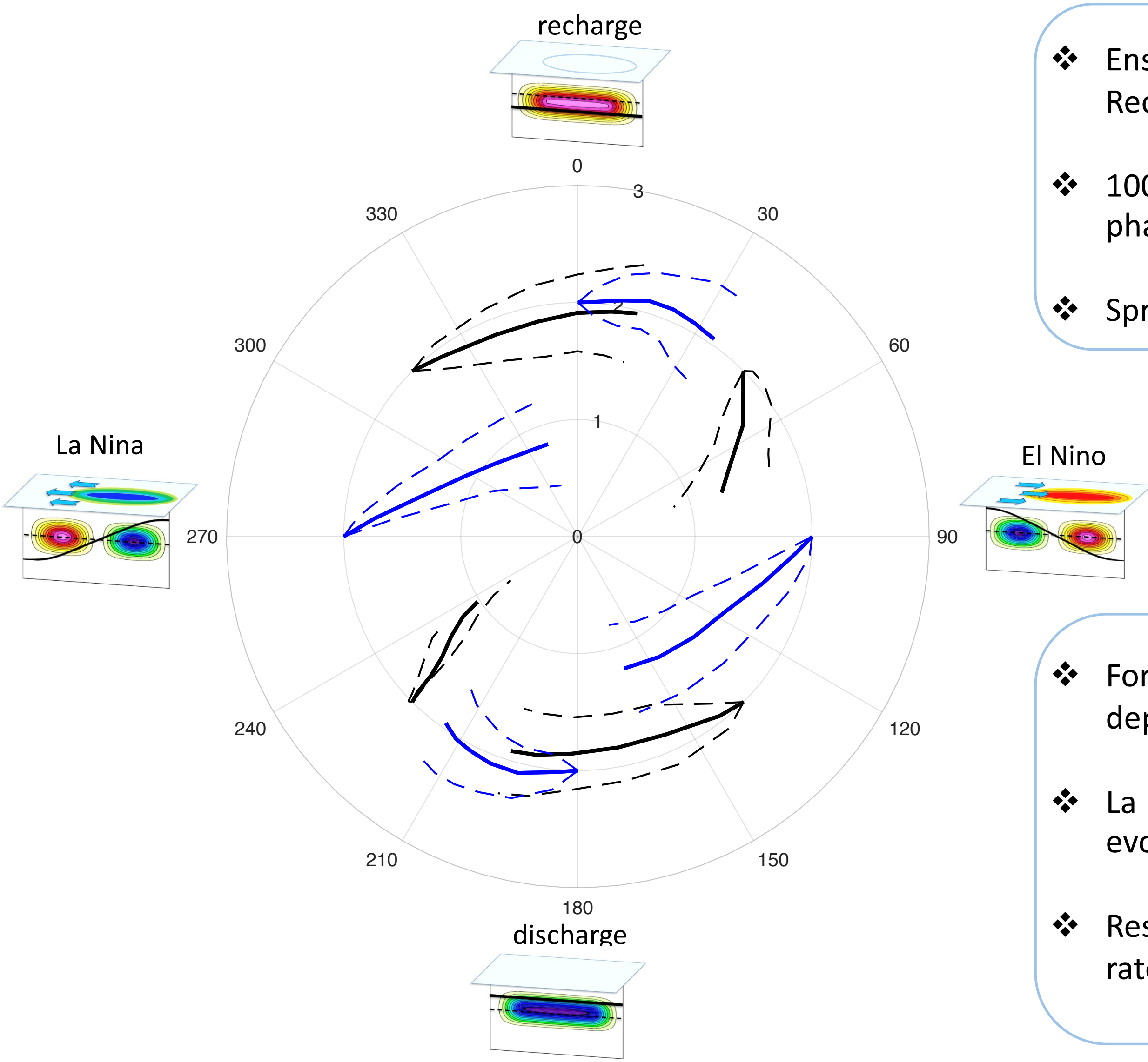
Predictability

Non-linear Recharge Oscillator



- Ensemble restarts with the non-linear Recharge Oscillator model
- 100 members start at S = 2 for 8 different phases and run for 6 month
- Spread in growth and phase evolution

- Forecast evolutions are strongly phase dependent
- La Nina state has very little phase evolution
- Results are consistent with the growth rate and phase speed characteristics.

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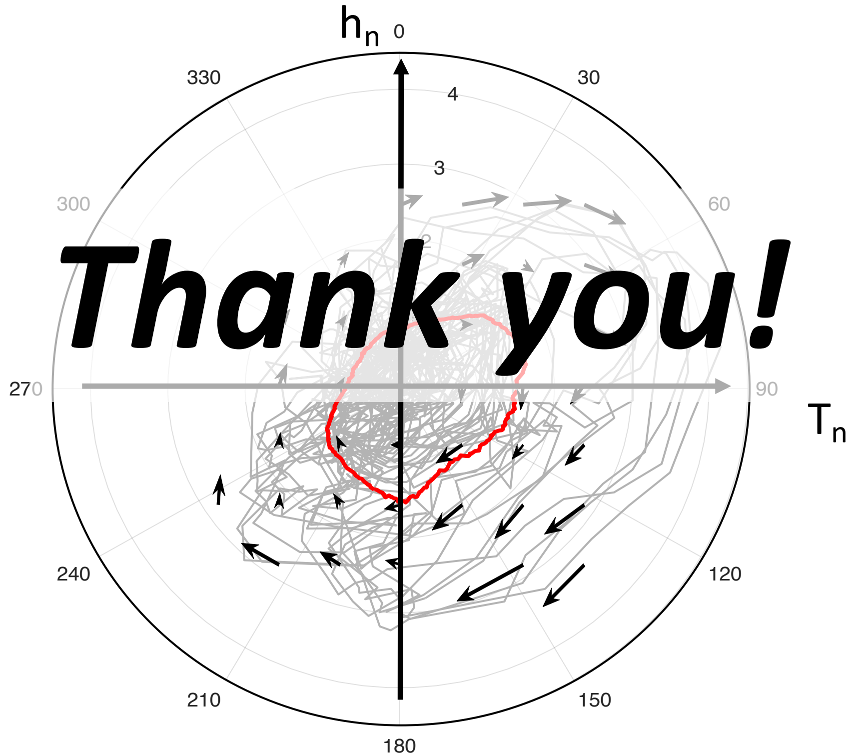
Summary

- The ENSO phase space is a good concept for understanding ENSO dynamics as a cycle
- It allows to define ***growth rate*** and ***phase speed*** as function of ENSO phase
- The observed ENSO phase space has strong asymmetries in probabilities, growth rates and phase speed
- Most of it is due to in-phase correlation between ***T*** and ***h*** -> artifact of estimating ***h***?
- Non-linear growth rate of ***T*** can explain much of the non-linearity, but not all of it

Outlook

- The physical phase space is a good concept for any climate mode (.e.g, MJO)
- Analysis of ***growth rate*** and ***phase speed*** as function of phase helps to understand the dynamics of a climate mode
- A positive phase speed in all phases indicate a ***true oscillator***

Asymmetries in the ENSO phase space



Thank you!

Dietmar Dommenget and Maryam Al-Ansari

soon to be published in Climate dynamics, keep fingers crossed!

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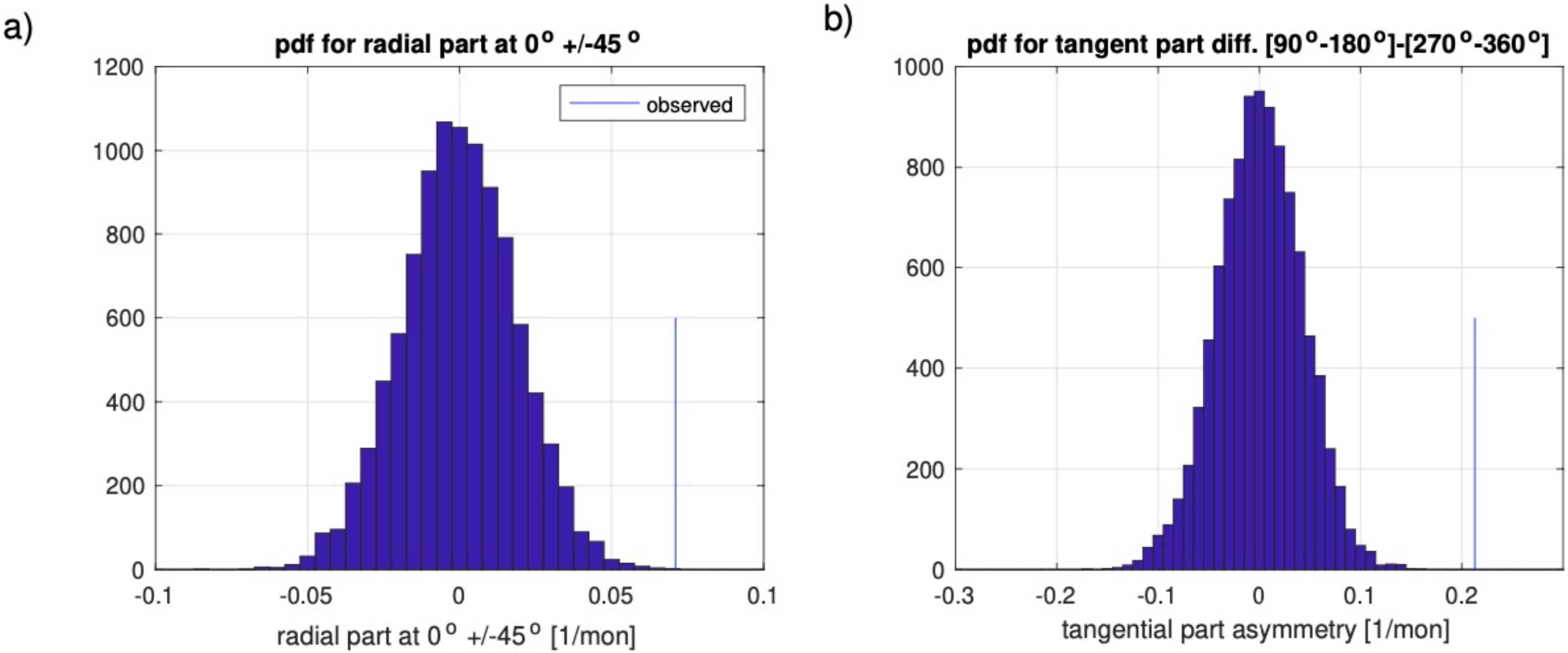


Figure 7: (a) Probability distribution for the radial tendency part at 0^o +/-45^o for the idealized ReOsc model and the observed value (blue vertical line). (b) Probability distribution for the difference of the tangential tendency part between [90^o- 180^o] minus [270^o- 360^o] for the idealized ReOsc model and the observed value (blue vertical line).

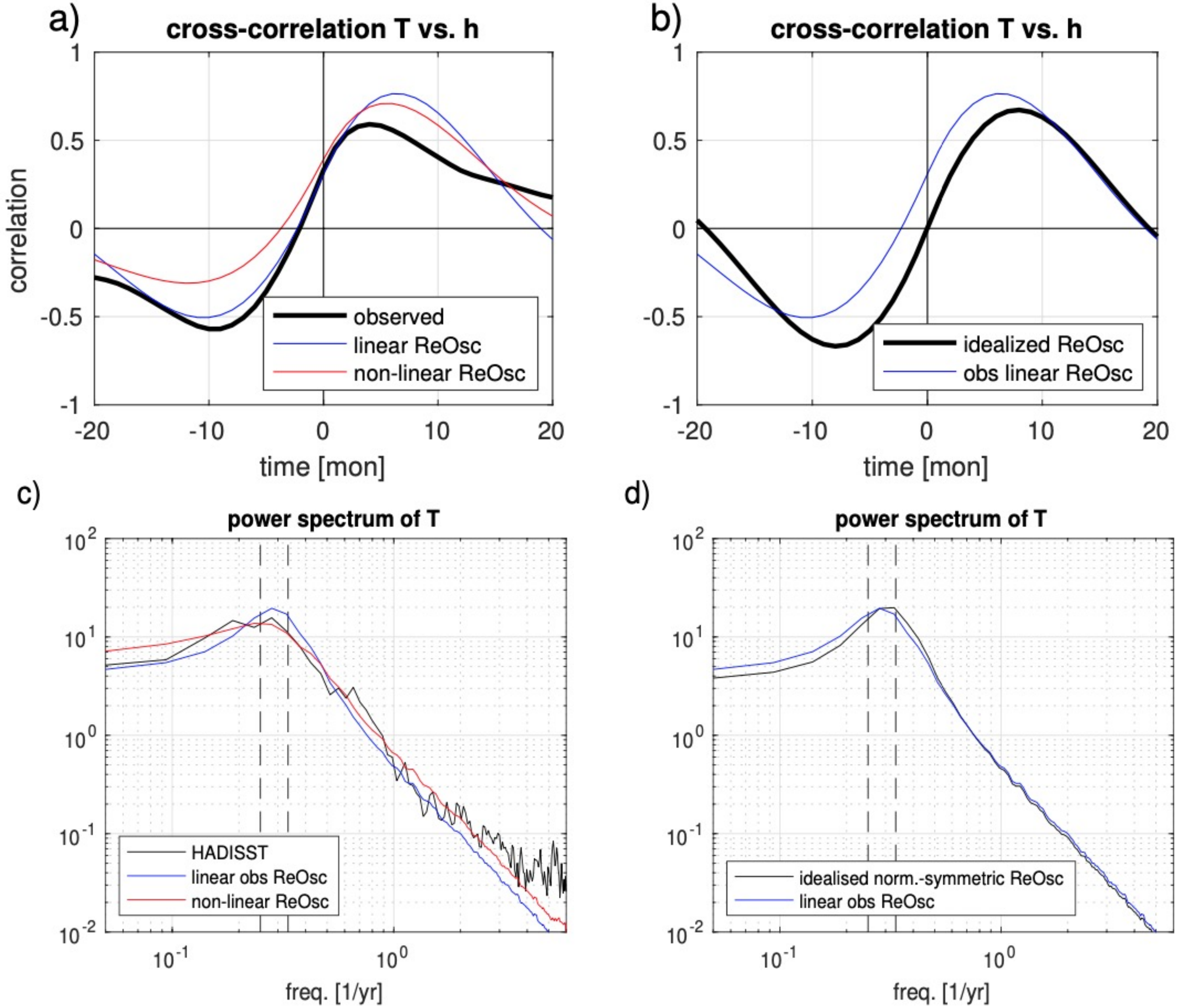
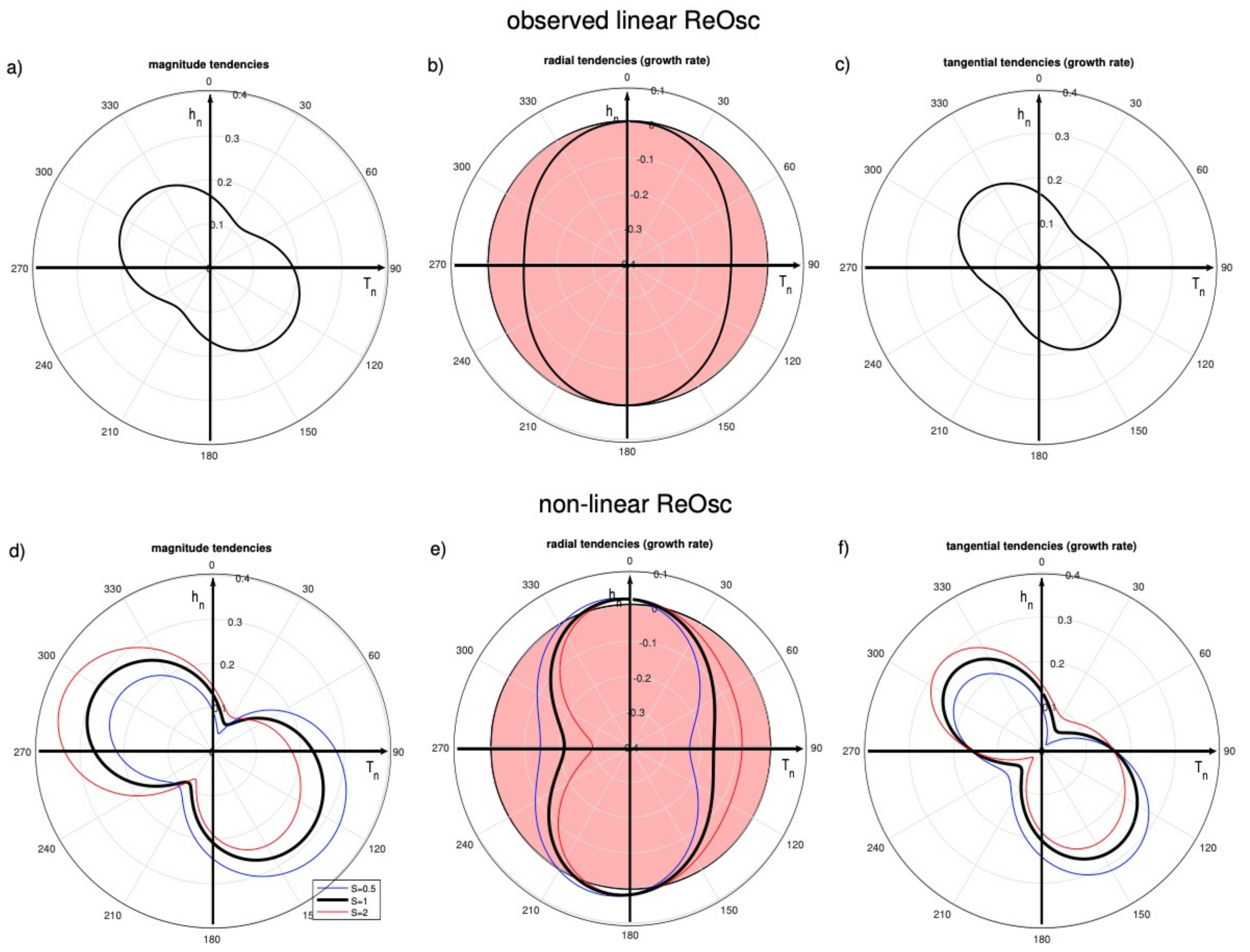


Figure 4: upper: cross-correlation between T and h for the observations and ReOsc models fitted to observations (a) and for an idealized ReOsc model (b). Negative lag time indicate T is leading the time evolution of h. Lower: power spectrum of T for observations (c) and for an idealized ReOsc model (d). The vertical dashed lines mark the periods of 3yrs and 4yrs.


observed linear ReOsc
a)
magnitude tendencies
b)
radial tendencies (growth rate)
c)
tangential tendencies (growth rate)
non-linear ReOsc
d)
magnitude tendencies
e)
radial tendencies (growth rate)
f)
tangential tendencies (growth rate)
S=0.5
S=1
S=2